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Laser Propulsion Support Program

Final Report

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PREPARED FOR PROPULSION DIVISION, GEORGE C. MARSHALL SPACE FLIGHT CENTER, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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LASER PROPULSION SUPPORT PROGRAM FINAL REPORT

AN ASSESSMENT OF AVAILABLE HIGH ENERGY LASER TECHNOLOGIES FOR NASA PROPULSION AND POWER BEAMING APPLICATIONS

November 1, 1980

Prepared for National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Propulsion Division, Marshall Space Flight Center, Alabama 35812.

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I. EXECUTIVE SUMMARY

OVERALL STUDY OBJECTIVE

The overall motive of this study is to provide a substantial rationale for NASA's participation in an expanded effort to develop and exploit high energy laser technology. A top level assessment of DoD high energy laser technologies is performed to investigate their relevance and potential for transfer to NASA propulsion and power beaming applications and areas for unique and complementary HEL research and development by NASA are identified.

The purpose of the present work is to help to establish a sufficient technical basis for NASA's involvement in high energy laser (HEL) research and development so that the advantages are clearly defined. It is important to realize, however, that the technical bases are complex, requiring attention to several different but interlocking factors. -- For an historical example, consider the diverse elements that had to be brought together in order to reach the moon: (1) taming of hydrogen-oxygen propulsion, (2) extreme miniaturization of computers, (3) development of fuel cell technology, (4) mastery of lunar orbital rendezvous, etc. Each of these elements was essential to the success of the mission, but their individual worth could not be understood without bringing them together to see how they reacted upon the total system effectiveness. -- In a similar manner, it is not sufficient to try to evaluate the worth of laser propulsion and power beaming by looking only at individual pieces of the puzzle. Joint considerations of efficiency, cost, synergistic potential, time of achievement, and overall national objectives must be made. Nor is it valid to look at individual physical accomplishments: If the objective were <u>only</u> to lift one kilogram of mass to the moon, there might be a hundred ways to achieve the goal. If the objective were to lift a billion kilograms to the moon, the overall justification would become paramount, and only one best approach would emerge.

Our work in this study is governed by the foregoing philosophy. The study represents a 4 man-month effort for the Propulsion Division of the NASA Marshall Space Flight Center primarily (1) to assess current and projected high energy laser technology programs funded by the Department of Defense, and (2) to determine potential transfer of these technologies to NASA applications in the areas of laser propulsion and power beaming.

Major laser system technologies are addressed; gas dynamic lasers, electric discharge lasers, chemical lasers, excimer lasers, free electron lasers, and large optical systems from a few meters to tens of meters in diameter -- both ground-based and space-based. NASA applications are defined in broad parametric terms covering launch requirements, mission duration, and technological risk.

The potential transfer of existing or projected DoD HEL technology to NASA applications is evaluated in terms of efficiency, cost, synergistic potential and time of achievement. Probable payoffs are highlighted, and recommendations are made for complementary research and development programs to reduce system development time and minimize cost to achieve earliest operational capability for both NASA and DoD.

OVERALL STUDY OBJECTIVE

TOP LEVEL EVALUATION OF THE ATTRACTIVENESS OF A LASER PROPULSION AND POWER BEAMING PROGRAM AT NASA AND POTENTIAL DOD TECHNOLOGY TRANSFER.

- ASSESS SYSTEM ELEMENTS
  - EVALUATE TECHNOLOGY
  - EVALUATE MISSIONS
  - COMPARE WITH OTHER OPTIONS
- ESTIMATE TOTAL SYSTEM EFFECTIVENESS BASED ON JOINT CONSIDERATION OF
  - EFFICIENCY
  - COST
  - SYNERGISTIC POTENTIAL
  - TIME OF ACHIEVEMENT
- INDICATE PROBABLE PAYOFFS
- RECOMMEND OVERALL PROGRAM DIRECTION

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LASER PROPULSION SUPPORT PROGRAM METHODOLOGY

The Laser Propulsion Support Program Methodology provides parallel assessments of technology development and mission definition for both civilian and defense applications. From these assessments an overall rationale for complementary research and development programs is developed.

An analysis of propulsion and energy transmission modes is performed in a manner which permits assessment of the ability of high energy laser systems to accomplish particular missions. Cost projections and schedules of DoD laser programs are developed and compared with NASA mission model projections.

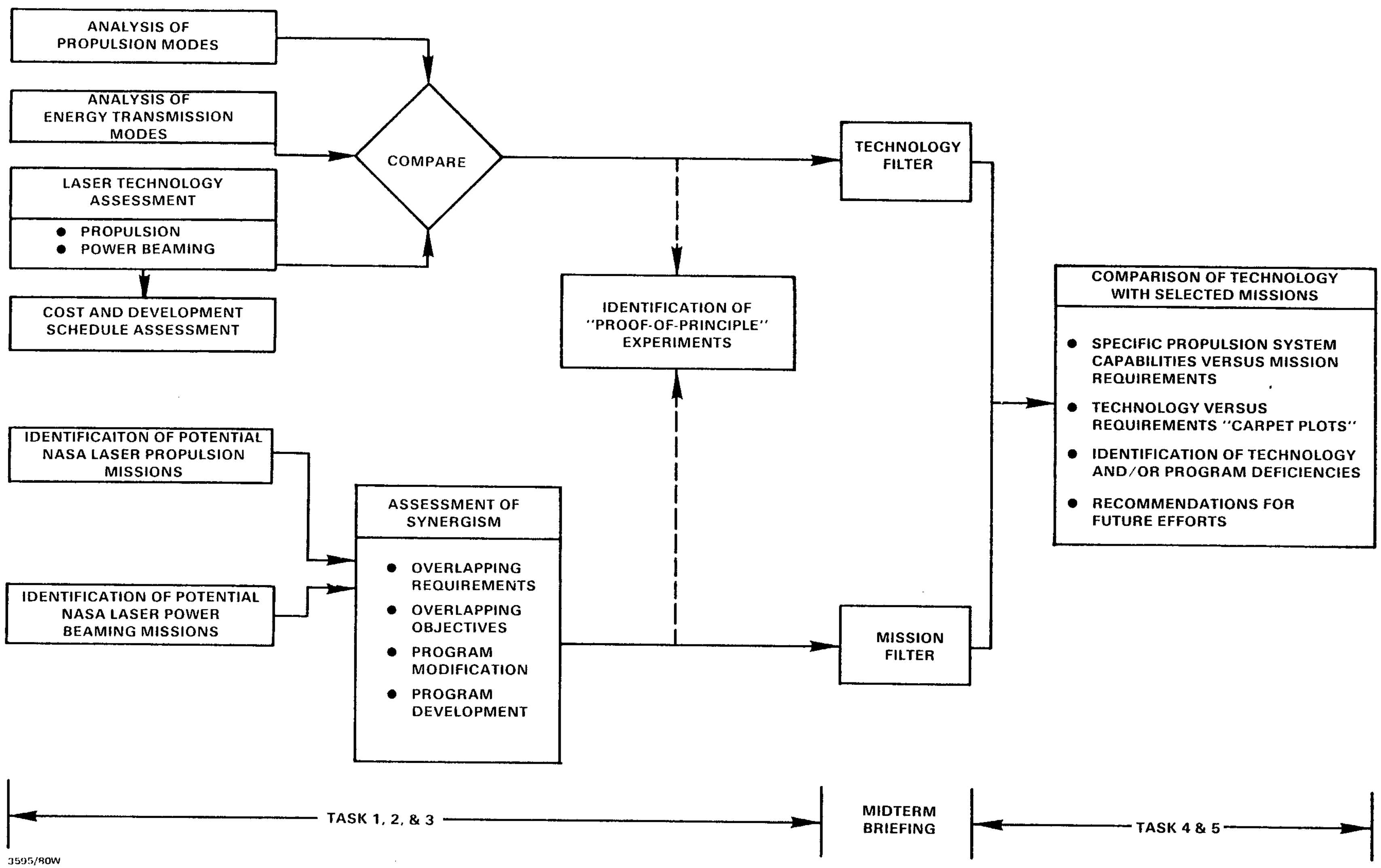
A parallel investigation is conducted to examine potential NASA laser propulsion and power beaming missions. Programs are analyzed to identify overlapping requirements and objectives and to scope potential program modifications and/or new program starts to alleviate any serious overlap.

Technology and mission "filters" are used to select the most important combinations for a more detailed comparison of technology transfer and future program requirements. Short wavelength lasers -- in particular Free Electron Lasers -- are considered for performing missions to raise payloads from low earth orbit to higher orbits.

Technology deficiencies are noted and recommendations are made for future efforts to either correct current program deficiencies or to fill technology "voids" through the initiation of new program thrusts.

The methodology has been applied in all of these tasks to a level of detail consistant with this first-cut study.

LASER PROPULSION SUPPORT PROGRAM METHODOLOGY



SUMMARY OF HIGH ENERGY LASER TECHNOLOGY ASSESSMENT (DEFENSE HEL TECHNOLOGIES)

Department of Defense High Energy Laser Programs are narrowly focused and address a restricted set of requirements.

The high energy laser programs of the Defense Department are scoped to address specific requirements of Air Force, Navy, and Army missions. This results in technology development that is narrowly focused and restrictive in terms of system capabilities. This is not to say that the DoD technology program is less demanding than one that could satisfy NASA needs. In fact there are certain areas, such as pointing and tracking, slew rates, command and control, etc., where military missions place requirements on a system that exceed those of most proposed civilian applications. On the other hand, certain civilian applications can be extremely demanding with regard to specific system performance levels, for example, the required laser run-time for propulsion or power beaming applications.

DoD laser programs are initiated in response to critical national security needs and hence tend to emphasize technologies available at the time the needs were established. Over the course of the last 12 years, various HEL devices have been studied. The current emphasis on space missions and the benefits of emerging shorter wavelength laser technologies have resulted in a shift in DoD emphasis to programs seeking to exploit chemical, excimer, and free electron lasers. The newer programs are still focused on relatively short run-time with very precise pointing and tracking requirements.

In addition to surveying the current state of technology development, the present study summarizes the state of system cost prediction for Air Force high energy lasers. Cost estimates of military laser systems are based upon models that project costs for relatively low power lasers and small optical systems compared with system requirements for most civilian applications. Extrapolations using these cost models should be made with great care.

SUMMARY OF HIGH ENERGY LASER TECHNOLOGY ASSESSMENT (DEFENSE HEL TECHNOLOGIES)

DOD PROGRAMS ARE:

- FOCUSED PRIMARILY ON HIGH POWER AIRBORNE AND SPACE-BASED LASER SYSTEMS WITH SHORT RUN TIME AND PRECISE POINTING AND TRACKING.

- EMPHASIZING CHEMICAL AND SHORT WAVELENGTH LASERS.

- MAKING COST ESTIMATES USING MODELS THAT PROJECT COSTS FOR RELATIVELY SMALL LASER SYSTEMS. EXTRAPOLATION TO LARGE SYSTEMS MAY NOT BE VALID.

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SUMMARY OF HIGH ENERGY LASER TECHNOLOGY ASSESSMENT (NASA THRUSTS)

> NASA laser programs should be broad based to develop long run-time lasers with large optical systems while minimizing weight in orbit. Accordingly, there is a strong case for application concepts based upon ground-based, long running lasers using erectable, Space Shuttle compatible optical systems to relay the laser energy to the user. Alternatively, direct solar pumped lasers may point the way to a short cut for deploying HELs in space.

The great majority of NASA laser applications require long run-time (from hours to days) with a pointing and tracking precision that is certainly technologically challenging but in general less than that required for most Defense Department missions. Long run-time relates directly to large system weights and volumes. This is the reason that DoD systems are designed to satisfy carefully derived airborne or space-based mission specific run-time constraints using compact, lightweight engineering methods.

The state of current laser technology suggests that NASA should focus on ground-based, continuous wave laser systems to eliminate the need for expensive and difficult space-based lasers and should rely on development of large orbiting optical systems to deliver the laser energy by utilizing a "relay" concept. This also reduces pointing and tracking requirements in that cooperative, large diameter optics are placed on precisely known orbital paths calculated to minimize demands on the ground-based laser systems. Short wavelength lasers should be used to minimize optical aperture sizes and to take advantage of atmospheric propagation benefits. These programs would also complement the current DoD emphasis, thus reducing development time and minimizing cost through shared program development.

The recent successful demonstration of a direct solar-pumped gas laser at NASA Langley Research Center opens some important new possibilities for developing simple and cost effective HELs for space deployment.

Either direct solar-pumped lasers or long running electric lasers should exploit the full benefits of the space environment. Electric lasers (EDLs, Excimers, FELs, etc.) would require either low specific weight solar or nuclear power sources in space. The rotating bed nuclear reactor is an emerging technology that promises hundreds of megawatts of power from a volume of a few cubic meters, making it a prime candidate for powering electrically pumped lasers.

Applicable system cost models must be developed for all of the above systems so that an honest comparison of cost effectiveness can be made with alternative systems.

SUMMARY OF HIGH ENERGY LASER TECHNOLOGY ASSESSMENT (NASA THRUSTS)

NASA PROGRAMS SHOULD:

- EXPLOIT THE POSSIBILITIES OF HIGH POWER, GROUND-BASED CW SYSTEMS USING RELAY OPTICS IN SPACE TO:
  - ELIMINATE WEIGHT AND VOLUME CONSTRAINTS ON LONG RUN-TIME LASERS;
  - DEVELOP LARGE (5-60 METER DIAMETER) ADAPTIVE OPTICS DEPLOYABLE WITH SPACE SHUTTLE AND HAVING LESS STRINGENT POINTING AND TRACKING REQUIREMENTS THAN DOD.
- EMPHASIZE SHORT WAVELENGTH LASERS (FEL, $\lambda \leqslant 2.2$ MICRONS) TO ACHIEVE:
  - VERY LONG RUN-TIME FOR EXTENDED MISSIONS:
  - COMPLEMENTARY R&D PROGRAM WITH DOD TO REDUCE DEVELOPMENT TIME AND MINIMIZE COST.
- AGGRESSIVELY DEVELOP DIRECT-PUMPED SOLAR LASERS FOR SPACE DEPLOYMENT
- EXPLOIT EMERGING ROTATING BED REACTOR TECHNOLOGY FOR SPACE-BASED HEL AND OTHER APPLICATIONS.
- DEVELOP APPLICABLE COST PROJECTION MODELS FOR ALL OF THE ABOVE SYSTEMS.

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SUMMARY: HEL MISSION AND TECHNOLOGY SYNERGISM

NASA and DoD missions can have high synergism. The development and exploitation of space laser technologies provides a logical development path for important civilian laser applications that can evolve into a major sustaining mission for NASA.

NASA applications and Defense Department missions and technologies can have high synergism. The technologies required for laser propulsion and power beaming can be carefully tailored to produce a system that will have the implicit capability to serve extremely useful and, in many ways, unique civilian purposes while also being able to accomplish the most demanding of the DoD missions.

The development and exploitation of these space laser technologies, especially thrusts to increase laser run-time and develop large optical systems that can be deployed in space, could evolve into a major sustaining mission for NASA. These programs would serve the nation by minimizing development and deployment costs for fulfilling both civilian space and energy needs and critical Defense needs.

A logical development path is evident that initially emphasizes ground-to-space applications to mature the laser and optical system technologies that can later be applied to the more demanding requirements of space-based systems. As the laser capability expands and more optical systems are placed in orbit, the requirement for sustained growth in US man-in-space activity will become evident. The "bootstrapping" effect of larger numbers of men and machines in space, working to solve critical defense and energy needs of our planet, will justify a national space program that will continue to expand in the future.

HEL SYNERGISM AND MISSION SUMMARY

- NASA AND DOD LASER MISSIONS AND TECHNOLOGIES CAN HAVE HIGH SYNERGISM.
  - — MISSION SYNERGISM
  - — APPLICATION SYNERGISM BETWEEN POWER BEAMING AND PROPULSION
- THE DEVELOPMENT AND EXPLOITATION OF SPACE LASER TECHNOLOGIES CAN EVOLVE INTO A MAJOR SUSTAINING MISSION FOR NASA.
- NASA CAN PERFORM A MAJOR SERVICE TO NATIONAL SECURITY BY DEVELOPING AND TESTING CIVILIAN-ORIENTED TECHNOLOGIES THAT ALSO HAVE HIGH PAYOFFS FOR DOD.
- THERE IS A LOGICAL DEVELOPMENT PATH FOR MAJOR CIVILIAN LASER MISSIONS LEADING FROM GROUND-TO-SPACE POWER BEAMING AND PROPULSION TO SPACE-BASED SYSTEMS.
- EXPANDING SPACE LASER CAPABILITIES "BOOTSTRAP" THEMSELVES TO HIGHER SIGNIFICANCE AND GREATER COST-EFFECTIVENESS.

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II. HIGH ENERGY LASER TECHNOLOGY ASSESSMENT

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HIGH ENERGY LASER TECHNOLOGY ASSESSMENT

> The Department of Defense has pursued a broad high energy laser technology program that has, over the past decade, developed gas dynamic lasers, both pulsed and continuous wave electric discharge lasers, and chemical lasers. Research and development is also underway for short wavelength advanced technology lasers known as eximers and Free Electron Lasers.

The Department of Defense (DoD) has spent nearly 1.5 billion dollars on high energy laser (HEL) development since the discovery of flowing gas lasers in 1968. Over one-half billion dollars has been spent in the last three years. Programs currently underway should lead to significant feasibility demonstrations in the next few years and should enable the DoD to make prototype development decisions in the mid-1980s.

Major defense programs that will be discussed in the following charts include the following:

ALL (Airborne Laser Laboratory): A KC-135 aircraft with a gas dynamic laser.
JSRT (Joint Short Range Test): A joint Air Force/Army electric laser test program.
SLTDP (Special Laser Technology Development Program): An Air Force advanced technology program.
Visible Laser Program: A DARPA program developing excimer and free electron lasers.
MOLLINJAR: An Air Force pulsed chemical laser program.
SIGMA: An Air Force cylindrical DF chemical laser.
ALPHA: A DARPA cylindrical HF chemical laser.
LAMBDA: A DARPA linear HF chemical laser.
NACL (Navy Advanced Chemical Laser): A Navy linear DF chemical laser.
MIRACL (Mid-Infrared Advanced Chemical Laser): A Navy linear DF chemical laser.
MTU (Mobile Test Unit): An Army continuous wave electric discharge laser.
ABEL (Air Breathing Electric Laser): An Army pulsed electric discharge laser.
VIPER (Variable Intensity Pulsed Effects Radiation): An Air Force pulsed electric discharge laser.

A broad technology assessment is developed in this section. Specific details of DoD programs and projections are contained in a classified report developed as part of this study effort: BDM/W-80-618-TR, "An Assessment of Potential Synergism Between DoD High Energy Laser Technology Development and NASA Applications (U)".

DEPARTMENT OF DEFENSE HIGH ENERGY LASER PROGRAMS

Department of Defense High Energy Laser Program emphasis has shifted to chemical and short wavelength lasers.

Numerous revisions are now taking place in the DoD laser effort. Major programs and their current status are as follows:

The Bireactant Gas Dynamic Laser may be regarded as an upgrade to the Gas Dynamic Laser scheduled to be flown in the ALL Cycle III test program in the Fall of 1980. The BGDL probably will not be built since there is a very good chance that the ALL program will be cancelled after the Cycle III experiments are completed.

The VIPER pulsed EDL is part of the Air Force/Army JSRT Program and the ALL Program. The Army has cancelled its support of JSRT and the Air Force is likely to do the same, hence the VIPER device will probably not be built. Carbon Dioxide (CO_2) continuous wave EDLs were developed as backup lasers to the GDL in the ALL program. CW EDLs are currently not being pursued by the Air Force.

Chemical lasers are receiving increased emphasis by the Air Force under DARPA funding. The SIGMA device will reach a critical power demonstration milestone this year. The MOLLINJAR program is a high-risk effort that also has to meet a critical experimental power milestone this year.

The Defense Advanced Research Projects Agency (DARPA) is funding three major laser device programs (ALPHA, LAMBDA and a Visible Laser Program) and two major optical programs (LODE and Talon Gold). ALPHA is a large, space-based cylindrical laser at 2.8 microns. The LAMBDA program has essentially been terminated. The visible laser program is concentrating on Excimers and Free Electron Lasers. The Air Force also has a program to study near/visible wavelength Iodine lasers (1.315 micron).

The Navy HEL program has developed linear Deuterium Floride chemical lasers over the past five years for shipboard applications. The development of the NACL device was completed in 1975. The MIRACL will demonstrate power levels a factor of four to five times greater than the NACL later this year.

The Army has drastically curtailed its HEL technology development since the cancellation of the JSRT program, which was to use the ABEL device technology. The ABEL program will probably be cancelled at the end of FY '80. The MTU was developed by the Army to test ground combat system concepts. It has been recently transferred to NASA Marshall for laser propulsion experiments. The Army is currently reevaluating its overall HEL requirements in light of an operational concept developed during the Army Laser Technology Assessment (ALATA) Study -- the Laser Forward Area Ground Demonstrator.

DEPARTMENT OF DEFENSE
HIGH ENERGY LASER PROGRAMS

DOD AGENCY	LASER TYPE	LASING MEDIUM	PROGRAM NAME/DESCRIPTION
AIR FORCE	BIREACTANT GAS DYNAMIC LASER	CO_2	PART OF THE AIRBORNE LASER LABORATORY PROGRAM
	PULSED ELECTRIC DISCHARGED LASER	CO_2	PART OF THE JOINT SHORT RANGE TEST (JSRT) PROGRAM AND THE AIRBORNE LASER LABORATORY (ALL) PROGRAM. (VIPER — VARIABLE INTENSITY PULSED EFFECTS RADIATION)
	CONTINUOUS WAVE ELECTRIC DISCHARGE LASER	CO CO_2	NOT BEING DEVELOPED — PART OF THE SPECIAL LASER TECHNOLOGY DEVELOPMENT PROGRAM (SLTDP) NOT BEING DEVELOPED — PART OF THE AIRBORNE LASER LABORATORY (ALL) PROGRAM.
	CYLINDRICAL CHEMICAL LASER	DF	SIGMA — PART OF THE SPECIAL LASER TECHNOLOGY DEVELOPMENT PROGRAM (SLTDP)
	PULSED CHEMICAL LASER	DF	ADVANCED CONCEPT — PART OF THE SPECIAL LASER TECHNOLOGY DEVELOPMENT PROGRAM (SLTDP)
DEFENSE ADVANCED RESEARCH PROJECTS AGENCY	CYLINDRICAL CHEMICAL LASER	HF	ALPHA
	LINEAR CHEMICAL LASER	HF	LAMBDA
	SHORT WAVELENGTH LASERS	VARIOUS ELEMENTS	ADVANCED CONCEPTS — VISIBLE, EXCIMER AND FREE ELECTRON LASERS (VISIBLE LASER PROGRAM)
NAVY	LINEAR CHEMICAL LASER	DF	NAVY ADVANCED CHEMICAL LASER (NACL) MID INFRARED ADVANCED CHEMICAL LASER (MIRACL)
ARMY	CONTINUOUS WAVE ELECTRIC DISCHARGE LASER	CO_2	MOBILE TEST UNIT (MTU)
	PULSED ELECTRIC DISCHARGE LASER	CO_2	AIR BREATHING ELECTRIC LASER (ABEL). PART OF THE JOINT SHORT RANGE TEST (JSRT) PROGRAM.

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LASER DEVICE TECHNOLOGY KEY POINTS

> Department of Defense HEL program objectives are narrowly focused to satisfy specific military mission requirements. Emphasis is being placed on chemical and short wavelength lasers. The future of civilian HEL applications depends heavily upon short wavelength (particularly Free Electron Laser) development.

The high energy laser program in the Department of Defense has experienced a number of changes in both program direction and emphasis. These types of programmatic oscillations are to be expected in any development programs addressing technology that is complex, dynamic and still subject to "technology breakthroughs." Gas Dynamic Lasers (GDL) were the first devices to show the promise of weapon-size power levels. It was obvious from the begining of their development that low specific power would limit their usefulness. Electric Discharge Lasers (EDL) were developed primarily as back-up devices for the GDLs. Unforseen problems in flow homogeneity and mode/medium interaction caused interest in their continued development to diminish. Also the requirement for a large energy source -- as much as 4 or 5 times the output power to be generated -- was always a limiting factor to their widespread use in military or civilian applications. The promise of high specific power and more compact cylindrical design resulted in initiation of programs for the development of chemical lasers. As the primary perceived military threat shifted to space targets, increasing support was obtained for the development of visible and other short wavelength laser devices. The latter lasers permit smaller optical systems to achieve required intensities at operationally useful ranges, and they also result in increased target vulnerability due to enhanced target interaction at the shorter wavelengths.

DoD HEL programs have always centered around systems that were thought to be achievable at the time featuring short run time, open-cycle, and self contained, lightweight construction. The emerging emphasis on space applications places heavy demands on the growing chemical and short wavelength laser programs. A recent important milestone is the successful demonstration of the Navy linear chemical laser (MIRACL). The ultimate fate of the chemical laser effort will be determined by the Air Force and DARPA cylindrical laser programs (SIGMA and ALPHA respectively).

An extremely important opportunity for an expanding HEL future lies in the emerging short wavelength laser programs: Excimer Lasers and Free Electron Lasers. The promise of high efficiency, smaller optics, tuneability for enhanced atmospheric transmission, and "simple" machines (no moving parts or turbulent gas flow) opens up a vast array of potential employment concepts for Free Electron Lasers if they can be shown to be scalable to high power.

LASER DEVICE TECHNOLOGY
KEY POINTS

- DOD PROGRAM OBJECTIVES ARE NARROWLY FOCUSED
  - — SHORT RUN TIME
  - — LIGHTWEIGHT ENGINEERING
  - — OPEN-CYCLE
  - — SELF-CONTAINED
- DOD EMPHASIS IS BEING PLACED ON CHEMICAL AND SHORT WAVELENGTH LASERS
  - — KEY TO CHEMICAL LASER FUTURE IS A SUCCESSFUL CYLINDRICAL LASER PROGRAM (SIGMA, ALPHA).
  - — SHORT WAVELENGTH PROGRAM IS JUST BEGINNING— PROMISE OF HIGH EFFICIENCY AT SHORT WAVELENGTH, SMALLER OPTICS, TUNEABILITY, "SIMPLER" MACHINES.
  - — SHORT WAVELENGTH LASERS ALLOW FOR GROUND-BASED SYSTEMS WITH LOW TRANSMISSION LOSSES.

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EXCIMER LASER TECHNOLOGY

> High efficiency, short wavelength excimer lasers exhibit some attractive system attributes for both civilian and military applications. The technology is high risk but worth the undertaking.

Excimer lasers are a class of lasers with potential for scaling to high peak and average power. These lasers operate in the visible and ultraviolet portions of the spectrum. Excimer lasers have been operated using excitation with electron beams, electron beam controlled discharges, and with fast electric discharge configurations.

A number of critical issues must be faced before successful scaling to high average powers can be accomplished. These issues include:

(1) Flow homogeneity (pressure differential $\sim 10^5$; temperature differential $\sim 10^3$),
(2) Uniformity of excitation (required for acceptable beam quality),
(3) Size and quality of the optical elements,
(4) Absorption of the laser wavelength by excited states and species formed during excitation,
(5) High power electron beams,
(6) Damping of acoustic vibrations,
(7) Difficulty of mode control in very high mode cavity.

Many of these issues are familiar for all flowing gas, high power lasers; and experience previously gained with other lasers will be useful in the excimer programs.

Development of excimer laser technology to produce large average power systems involves high technical risk. However, the possibility of an efficient system (greater than 10 percent) and the inherent short wavelengths (smaller optics, less weight and volume, enhanced atmospheric transmission) are attractive systems aspects which indicate that this is a risk worth taking.

EXCIMER LASERS

TECHNOLOGY

- RESEARCH CENTERED ON XeF, KrF, HgCl
- CW ELECTRON BEAM PUMPED EXCIMER FUNDED BY DARPA
- KrF SYSTEM BEING BUILT BY LASL FOR DOE

CRITICAL ISSUES FOR HIGH POWER

- FLOW HOMOGENEITY $\left(\frac{\Delta P}{P} < 10^{-5}, \ \frac{\Delta T}{T} < 0.03°K\right)$
- UNIFORMITY OF EXCITATION (NONUNIFORM GAIN AFFECTS BEAM QUALITY)
- SIZE AND QUALITY OF OPTICAL ELEMENTS
- ABSORPTION OF LASER WAVELENGTH BY SPECIES IN THE MIXTURE
- HIGH POWER ELECTRON BEAMS
- DAMPING OF ACOUSTIC VIBRATIONS (LIMITS PULSE REP. RATE AND THUS HIGH AVERAGE POWER)

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FEL TECHNOLOGY

> The rapidly emerging Free Electron Laser (FEL) technology is an important new entry into the HEL arena. FELs present the potential for very efficient, tuneable, short wavelength, long running, high power lasers by the end of the 1980's. Successful development of FELs will have major impact upon the feasibility of civilian laser missions.

As part of an expanding visible laser R&D thrust, DARPA is funding FEL technology programs at Los Alamos Scientific Laboratory (LASL), Mathematical Sciences Northwest, Inc. and TRW, Inc. These programs are attempting to use existing linear electron accelerators and CO_2 laser excitation to demonstrate multi-kilowatt, short duration (a few nanoseconds) FEL pulses with a single pass energy extraction efficiency of better than 10 percent by Fall, 1981. The LASL program will subsequently demonstrate an energy recovery "racetrack" scheme that will hopefully result in an overall system efficiency of 30 to 50 percent by the Fall of 1983. LASL has proposed additional phases to this technology development program, as shown here, that would demonstrate a 10 megawatt, continuous wave FEL by the end of this decade at a total cost of approximately $87 million.

The critical underlying technology for FEL development is the mature, 50 year old particle accelerator technology. Optical energy is extracted from the electron beam using adiabatic capture of electrons by the electromagnetic field of the light wave, a phenomenon well understood in microwave tubes. Resonant coupling is established by forcing the electrons to radiate coherently in a periodic magnetic field known as a "wiggler". In the LASL design, the optical section is followed by a linear decelerator which recovers the unused electron energy by converting it to rf power and returning it to the accelerator, thus increasing overall efficiency of the system. The result is a conceptually simple machine that uses mostly proven techniques developed in related fields.

The FEL can be made a frequency tuneable device by varying the electron beam energy or wiggler magnet strength. This permits easy compromise between atmospheric transmission, focusing at long ranges and mirror performance. The FEL has already been demonstrated at Stanford University and dramatic improvments seem possible with modest refinements and extensions of present technology. Questions such as achievable beam quality and the magnitude and control of instability thresholds with large machines are being addressed. Areas receiving immediate attention are wiggler design, including the effects of transverse momentum spread, space charge and micropulse structure; optical/FEL system design, including diffraction effects to achieve optimal design of the wiggler/resonator combination; and injector design, so that trade-offs between beam brightness and peak current on the one hand and wiggler/resonator design on the other can be assessed. A coordinated program should be vigorously pursued by this country to achieve an operating multimegawatt FEL in the shortest possible time for the least total expenditure.

FEL TECHNOLOGY

(LOS ALAMOS SCIENTIFIC LABORATORY EXPERIMENT)

PHASE I. (FY80-83) ($6.6 M)	SMALL SCALE DEMONSTRATION (5KW DEVICE) • EXTRACTION EFFICIENCY EXPERIMENT CO_2 LASER, 5N SEC PULSE, 20-22 PERCENT EFFICIENT SINGLE PASS LINAC, 20 FOOT LONG STABLE RESONATOR. • ENERGY RECOVERY (RACETRACK) — 30 TO 50 PERCENT OVERALL EFFICIENCY.
PHASE II. (FY84-87) ($30 M)	PULSED HIGH POWER DEMONSTRATION (10 MW DEVICE) • 100 MICROSECOND PULSE, RELOCATE ACCELERATOR DUE TO RADIATION • 3 FOOT DIAMETER, 100 METER LONG ACCELERATOR • 300 METER LONG OPTICS • ONE CAVITY PER MEV AT 1.3 GHZ (8 MEV/METER MAXIMUM)
PHASE III. (FY86-89) ($50M)	CW HIGH POWER DEMONSTRATION (10 MW DEVICE) • ADVOCATED BY LASL • THEORETICAL PROJECTION FOR BEAM QUALITY • RAISE INSTABILITY THRESHOLD THROUGH CAVITY DEVELOPMENT • SCALABILITY — INCREASE LENGTH, INCREASE CURRENT? • PRODUCTION — 3 TO 4 YEARS PER COPY, POWER STATIONS ARE DRIVER.

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III. ADAPTIVE OPTICS TECHNOLOGY ASSESSMENT

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ADAPTIVE OPTICS TECHNOLOGY ASSESSMENT

Adaptive optical systems occur naturally in living animals, yet man has only recently appreciated their worth and begun to develop the technologies necessary for their realization in advanced optical systems.

"Adaptive optics" is a general term for optical components whose characteristics are controlled in real time based on operating experience to modify optical wavefronts resulting in optimimum system performance. Past history in optical technology has consisted of fixed optical components such as lenses, mirrors, and prisms. Fixed optical elements are satisfactory for a number of applications in which the operating conditions can be controlled or at least adequately specified. In an increasing number of applications, however, environmental stress and random processes may dominate the performance of an optical system. Current examples of such applications are: 1) large ground-based telescopes whose angular resolving power is limited by atmospheric turbulence, 2) large telescopes orbiting in space which suffer thermal and gravitational stresses, and 3) optical systems for high-energy lasers whose wavefronts are deformed due to thermal effects in the components or in the propagation path.

The performance and reliability of many functional systems for these applications, especially the high energy laser application, can be vastly improved by the use of closed-loop feedback systems. It is interesting to note that many animals, including man, rely on a adaptive optical imaging system for their eyesight, using a flexible lens of variable focal length, operated by muscular power and controlled by signals from the brain. Thus, the system functions as a closed loop to maximize the acuity of the image on the retina. The point is that active optical devices have evolved in nature. After years of developing conventional rigid optics, man is just becoming conscious of the possibilities that they afford.

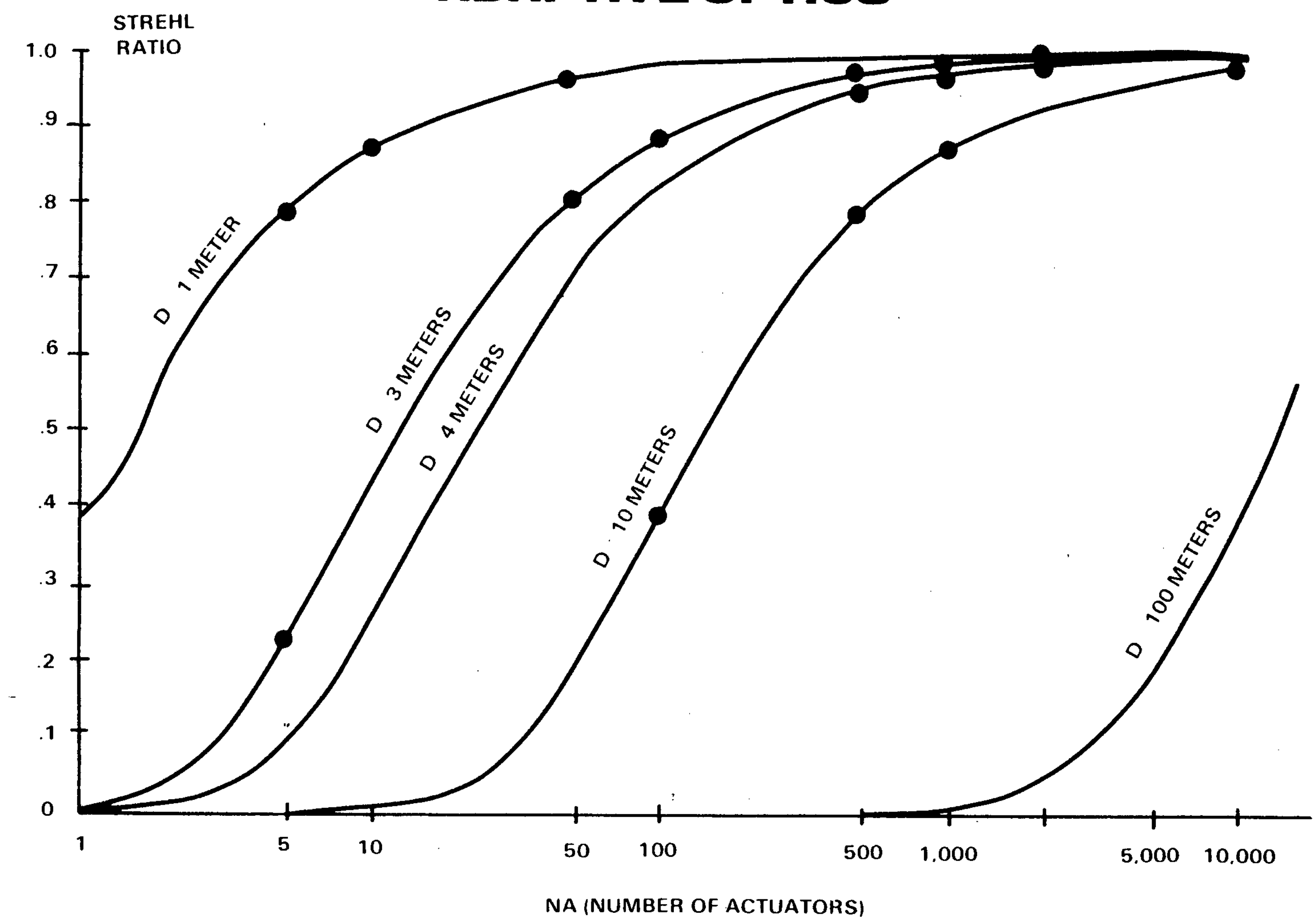
ADAPTIVE OPTICS

Strehl ratio can be used to compare the design and performance of adaptive optical systems with theoretically perfect optics. Operational employment requirements at a specific Strehl ratio are an equally important measure-of-merit.

The control of wavefronts is essential in high energy laser optical systems that propagate and concentrate energy to produce a high power density at a specific location for weapon or power beaming applications. Three basic components are required: a wavefront-modifying device, which may be reflective or refractive; a measuring device that accepts light and provides an output related to the property being optimized; and an information-processing device that accepts the measured data and converts it into the appropriate control signals for the wavefront-modified device. The exact arrangement of these basic components depends on the purpose of the specific system. There are two approaches for systems that operate at a single wavelength, e.g., lasers. One is phase conjugation where the beam initially reaching the target gives rise to reflection from small areas producing glints which generate spherical waves. These reflected waves traverse the propagation path in the reverse direction and consequently are spatially modified by the turbulence in the same way as the transmitted beam. The other is the aperture tagging approach in which trial perturbations are made in the outgoing wavefront and the optical power returned from a glint at the target is analyzed to determine which perturbations increase the power density. These perturbations are added to the wavefront and the process continues iteratively until the power density is optimized.

A commonly used figure-of-merit to evaluate adaptive optical systems is the Strehl ratio: the ratio of the actual peak intensity of a laser spot to that obtained with a perfect diffraction limited system. Strehl ratio for an adaptive optical system can be obtained as a function of optical diameter and number of acuators as shown here. Trade-offs can be made between diameter and numbers of actuators for a given Strehl ratio. For example, a Strehl ratio of 0.8 can be obtained with a 3 meter diameter system that incorporates 50 actuators or a 10 meter diameter system that incorporates approximately 500 actuators. The performance flexibility of these two optical systems is not the same, however. The 10 meter diameter system can deposit the same peak intensity at over three times the range of the 3 meter diameter system.

ADAPTIVE OPTICS



4504/80W

ADAPTIVE OPTICS TECHNOLOGY

Adaptive optics technology is rapidly progressing to develop systems for HEL military applications. Programs should be pursued to extend the state-of-the-art to larger diameter optics for civilian applications while providing a performance enhancement for broader military needs.

A summary of accomplishments in adaptive optics technology is shown here. The largest adaptive mirror constructed to date is a 75 centimeter diameter, segmented optic built by Perkin Elmer. Hughes has built and tested a 30 centimeter diameter, water cooled optic. These systems incorporate approximatley 70 to 120 actuators distributed over deformable zones or elements.

There is no doubt that some form of space erectable optical system will be required for high orbit, long-range applications. Most NASA missions require adaptive optical systems of a few meters to tens of meters in diameter. As indicated the largest single aperature that can be carried into orbit using the Space Shuttle is a 4.5 meter diameter. Rockwell has studied possible modification to the Shuttle main tank to accomodate single aperture diameters of up to 10 meters. Larger apertures would have to be assembled in space.

Adaptive optical systems with bandwidths suitable for military HEL applications (350 Hertz) have been demonstrated in a laboratory environment. Modal control of tilt, focus and astigmatism have also been verified using passive targets. Evaluation in more realistic experiments involving dynamic tracking scenarios is planned in future tests at the Air Force Weapons Laboratory using the Tracker Breadboard Test System (TBTS).

A critical adaptive optics issue that can be resolved only by hardware test is verification of shared aperture tracking by the laser beam and sensing device, particularly performance of the aperture sharing element. Sampling diffraction gratings have been fully tested with HEL beams but have not been used for passive tracking or imaging. Dichroic beam samplers specifically designed for shared/adaptive optics applications have been designed and fabricated. Alternative adaptive optical sensor techniques need to be comparatively evaluated in closed loop adaptive optics experiments to establish and verify optimum aberration sensing techniques.

DARPA is funding optical programs that will demonstrate achievement of specific performance levels required for critical military missions (LODE and TALON GOLD). Two tasks remain, however: (1) to construct an on-orbit, high power, accurate pointing and tracking system, and (2) to encourage the necessary technology programs to increase optics diameters to tens of meters and to further reduce pointing and tracking accuracy by an order of magnitude. This will enable geosynchronous stationing of reasonably sized optical systems that can accomplish many civilian applications while greatly expanding military effectiveness as well. There are many important and logical roles for NASA in this endeavor.

ADAPTIVE OPTICS TECHNOLOGY

- MAXIMUM SYSTEMS TESTED
  - 75 CM. DIAM., SEGMENTED, 37 ELEMENTS—PERKIN ELMER
  - 30 CM. DIAM., DEFORMABLE, 61 ZONES, WATER COOLED—HUGHES
  - COMPENSATED IMAGING SYSTEM FOR ARPA/MAUI TELESCOPE—ITEK
  - LARGEST (NON-ADAPTIVE) GROUND BASED TELESCOPE = 6 METERS—USSR
  - LARGEST SINGLE APERTURE TO FIT SPACE SHUTTLE BAY = 4.5 METERS
- MAXIMUM ACCOMPLISHMENTS
  - BANDWIDTHS OF 350HZ.
  - MODAL CONTROL OF TILT, FOCUS, ASTIGMATISM
  - EDGE ALIGNMENT OF SEGMENTS (FEW NANORADIANS)
  - MIRROR TEMPERATURES $>$100°C (LIMITED BY COATINGS)
  - SURFACE REFLECTANCE $>$99.9%

4504/80W

IV. LASER AND OPTICS TECHNOLOGY DEVELOPMENT SCHEDULES

4504/80W

LASER AND OPTICS TECHNOLOGY DEVELOPMENT SCHEDULES

Department of Defense high energy laser programs currently underway are intended to provide significant operational system feasibility demonstrations in the next few years and will enable the DoD to make prototype development decisions in the mid-1980s. Specifics of these program schedules are included in a classified volume written as part of this study effort, BDM/W-80-618-TR, "An Assessment of Potential Synergism Between DoD High Energy Laser Technology Development and NASA Applications." This document also includes a description of the two major military efforts to develop space-based adaptive optical systems (LODE and TALON GOLD).

Shown on the following chart is a development program for free electron lasers (FEL's) that has been proposed by the Los Alamos Scientific Laboratory. As previously stated, this new candidate laser for high energy, long run-time applications may be the needed "breakthrough technology" for civilian applications. If current experiments prove that high efficiency and scalability to high power levels are readily achievable, it is of utmost importance for the United States to undertake new programs to exploit the full potential of this opportunity. Since FELs presently represent only a small fraction of the DoD laser budget, an aggressive research and development program in the civilian sector could lead rapidly to the most general utilization of this pivotal laser technology.

FEL DEVELOPMENT SCHEDULE

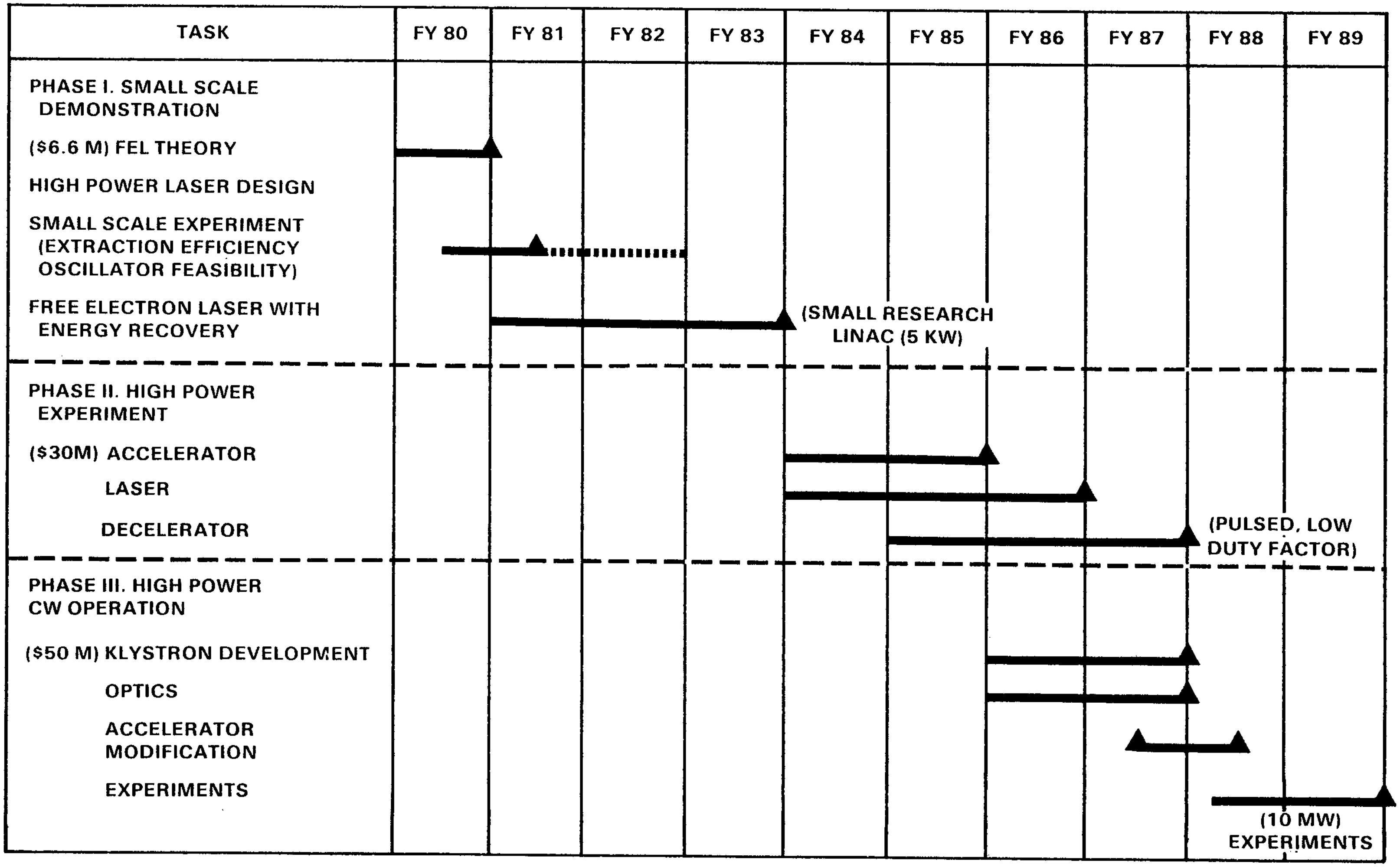
> The technology required to develop a multimegawatt, high efficiency, long running, Free Electron Laser is within the current state-of-the-art. If current experiments are successful, the device can be built by 1987 with sufficient program emphasis.

The Free Electron Laser technology development schedule shown here was formulated by the Los Alamos Scientific Laboratory (LASL). LASL, Mathematical Sciences Northwest (MSNW), and TRW are being funded by DARPA to complete the small scale extraction efficiency experiments, by mid FY81 as shown. Total funding for LASL to complete the experiment and demonstrate a 5 kilowatt FEL using a small research linear accelerator (linac) is $6.6M.

In Phase II LASL plans to design and fabricate a pulsed FEL as a high power experimental milestone in the eventual development of a 10 megawatt continuous wave device. Approximately $80M is required to complete this program by the end of FY89. In developing this schedule, LASL completed a conceptual design of a 10 megawatt (average power) FEL operating at a wavelength of 1 micron with greater than 10 percent efficiency. These design efforts showed clearly that such a laser was possible using very reasonable extrapolations of existing technology. Problem areas identified and now being addressed under DARPA funding are general FEL theory, including real (non-ideal) effects such as space charge and collective oscillations, and accelerator analysis in the areas of injector design and beam dynamics.

LASL believes that the development program shown here is conservative. Phase II accelerator and laser design could begin immediately after a successful extraction experiment in the fall of 1981 and thereby shorten the overall program by at least two years.

FEL DEVELOPMENT SCHEDULE*



*UPDATE FROM LA-UR-79: 904, A PROGRAM FOR FEL RESEARCH, LOS ALAMOS SCIENTIFIC LABORATORY

4504/80W

V. LASER AND OPTICS COST ESTIMATES

4504/80W

LASER AND OPTICS COST ESTMATES

> There are two models for estimating the life-cycle cost of HEL systems; one for airborne applications (CALIPER II), and one for ground and space-based applications (SLLICC). Neither of these models is designed to estimate costs for development, production and operation and support of large laser and optical systems required for most NASA applications.

In 1974, the Air Force initiated development of an airborne high energy laser system computer cost model. Since that time, the model has undergone numerous modifications and updates to reflect technology changes and to improve its efficiency and useability in terms of computer run time and output format. The current model is called CALIPER II. Recently, the Air Force developed another high energy laser cost model to make cost projections for ground-based and space-based lasers called SLLICC.

The structure of these models incorporates a two-dimensional chart of accounts that maps a work breakdown structure with the basic life-cycle categories. The work breakdown structure defines individual cost elements to ensure that all costs are taken into account. The basic life-cycle categories include the validation and full-scale development aspects of a Research and Development phase, a Production phase, and an Operations and Support phase.

In making estimates for laser systems applicable to NASA applications CALIPER II and SLLICC cost relationships are extrapolated well beyond the limits established when they were developed. Thus, any cost figures should be carefully analyzed for their reasonableness. Careful note should also be made of the limiting assumptions that are violated. The intent in extending cost projections beyond the model design limits is to make a first excursion to cost systems that have not been seriously costed before. Educated thought and judgement must be exercised to place a level of credibility on the resultant cost numbers.

SOURCES FOR LASER SYSTEM COST DATA

Careful note should be made of the limitations and assumptions inherent in current high energy laser system cost models.

Options are available in both CALIPER II and SLLICC to define each major subsystem by user input; the laser device, optics, fluid supply, control electronics (avionics), auxiliary power (for electric discharge lasers), or orbit maneuvering system for space-based systems.

Three generic types of lasers are modeled in CALIPER II; bireactant gas dynamic (BGDL), deuterium floride chemical (DFCL) and carbon monoxide or carbon dioxide electric discharge (EDL). The BGDL and DFCL are linear, open cycle, continuous wave devices. The EDL can be a combination of open or closed cycle, continuous or pulsed. There is increasing uncertainity in cost projections for these laser devices when power levels above 3 megawatts are used.

Turret modeling is either on-gimbal cassegrain or coelostat. Adaptive optics are costed by diameter size and number of actuators. Caution should be exercised, however, for large optical systems since the cost relationships were developed using diameters of less than 65 centimeters.

Fluid systems are costed based on input of laser device power, specific power and lasing time or directly from input of flow rates for each fluid specified.

Operations and Support costs are obtained from either detailed inputs from the Air Force Logistic Support Cost Guide or by application of a simple percentage of appropriate production phase cost elements.

The laser device cost estimates in SLLICC, are based on an open cycle, flowing gas, linear chemical laser. A cost increase factor of 1.4 to 2.0 is used to account for lightweight engineering. The space borne primary mirror is not adaptive. An orbit maneuvering system based on the Space Shuttle is modeled if a maneuvering spacecraft is selected.

SOURCES FOR LASER SYSTEM COST DATA

I. CALIPER II — COST ANALYSIS OF LASER INVESTMENT, PRODUCTION, ENGINEERING AND RESEARCH.

- AIR FORCE AIRBORNE LASER COST MODEL
- FULL TEN-YEAR LCC — R&D, PRODUCTION, OPERATION AND SUPPORT
- MAJOR SUBSYSTEM DEFINITION — LASER DEVICE, OPTICS, FLUID SUPPLY, CONTROL ELECTRONICS, POWER SUPPLY (EDL)
- CER LIMITATIONS — 3 MW POWER, 65 CM OPTICS

II. SLLICC — SPACE LASER LIFE CYCLE COST.

- AIR FORCE GROUND-BASED AND SPACE-BASED LASER COST MODEL
- FULL TEN-YEAR LCC — R&D, PRODUCTION, OPERATION AND SUPPORT
- MAJOR SUBSYSTEM DEFINITION INCLUDES SPACECRAFT AND SHUTTLE-TYPE OMS
- CER LIMITATIONS — SAME AS CALIPER II PLUS LASER IS OPEN CYCLE, LINEAR, FLOWING GAS, CHEMICAL AND SPACE-BORNE PRIMARY MIRROR IS NOT ADAPTIVE.

4504/80W

AVERAGE GROUND BASED VERSUS SPACE BASED TEN YEAR LIFE CYCLE COST

Space-based lasers appear to be at least a factor of two to three times more expensive than ground-based lasers.

An interesting comparison can be made between ground-based (GB) and space-based (SB) laser systems to develop an appreciation for the cost differential than could be expected from differences in the laser basing concept. A ground-based and a space-based system are compared in this table. Each of the laser systems is an identical 5 megawatt, 4 meter optics configuration. For the ground-based system, two lasers are built during the R&D phase (2-GB). Thus, there are Validation and Full Scale development costs but no production phase. The space-based system consists of 11 lasers in-orbit with an additional 11 replacement systems over the 10-year life-cycle (22-SB). Average "per unit" costs are presented for the space-based systems in the production phase. The cost of two space-based systems ($120M) is added in the "2-unit total" SB column to the Validation and Full Scale Development costs for comparison with the two ground-based systems.

The space-based system is an overall factor of 3.0 more expensive than the ground-based system. Major cost differences occur in the areas of system engineering integration and management (factor of 4.9 more expensive) and overall operation and support where the space-based system is self-supporting on-orbit therefore showing a factor of 26 less expensive than the ground-based system on a per-unit basis.* If one compares "site preparation" for the ground-based system with "launch vehicle, spacecraft, and integration" for the space-based system (essentially the activity required to place the system "on-site"), the large Operation and Support difference is partly neutralized with the space-based system being a factor of nearly 12 more expensive than the ground-based system. If these two extreme differences are not considered, the ground-based system is still about 2.6 times less expensive than the space-based system.

* This assumption itself may be highly questionable, but it is important to ponder the fact that any ground-based system will have a permanent, "hands-on" staff. Hence the high recurring cost of ground based systems may lead to less cost-effectiveness in the long run than space based systems running on free sunlight. Much more work is needed in this important area.

AVERAGE GROUND BASED VERSUS SPACE BASED TEN YEAR LIFE CYCLE COST * (MILLIONS OF 1979 DOLLARS)

HARDWARE ITEM	VALIDATION		FULL SCALE DEVELOPMENT		PRODUCTION		O&S		2 UNIT TOTAL		
	GB	SB	GB	SB	GB	SB	GB	SB	GB	SB	
LASER SYSTEM (2-GB) (22-SB)	190	350	160	260	—	60 (PER UNIT)	—	—	350	730	THE GROUND BASED SYSTEM IS: FACTOR OF 2.1 CHEAPER
SYSTEM ENGINEERING, INTEGRATION, MANAGEMENT	48	168	42	200	—	38 (PER UNIT)	—	—	90	444	FACTOR OF 4.9 CHEAPER
OPERATION AND SUPPORT (PER UNIT)	—	—	—	—	—	—	158	6	158	6	FACTOR OF 26 MORE EXPENSIVE
SYSTEM TEST AND EVALUATION	10	16	9	16	—	—	—	—	19	32	FACTOR OF 1.7 CHEAPER
AGE (GROUND C^3 EQUIPMENT, PECULIAR SUPPORT EQUIPMENT	10	(12)	8	(9)	—	(13) PER UNIT	—	—	18	(47)	FACTOR OF 2.6 CHEAPER
SITE PREPARATION (LAUNCH VEHICLE, SPACECRAFT, INTEGRATION)	38	(400)	38	(160)	—	(170) PER UNIT	—	—	76	(900)	FACTOR OF 11.8 CHEAPER
									711	2159	OVERALL FACTOR OF 3.0 CHEAPER

*HELTAS, VOLUME IV, B, ANNEX A2, TABLE A2-21 AND A2-24.

ADAPTIVE OPTICS COST

> There appear to be two important trends in the cost of adaptive optical systems: (1) sensitivity to additional actuators decreases as mirror diameter increases and (2) doubling the cost of an optical system buys more than a factor of two improvement in system performance.

The CALIPER II adaptive optics cost relationship incorporates the following independent parameters: the laser cavity beam diameter, the number of actuators, and the total number of systems procurred. This chart is a plot of the results of this cost estimating relationship for the 10-year life-cycle cost of 10 adaptive optical units. Cost in millions of 1980 dollars is plotted (dotted curves) for varing optics diameter for a given number of adaptive actuators as an overlay on a plot of optical performance as measured by Strehl ratio for a given optical diameter and number of actuators (solid curves).

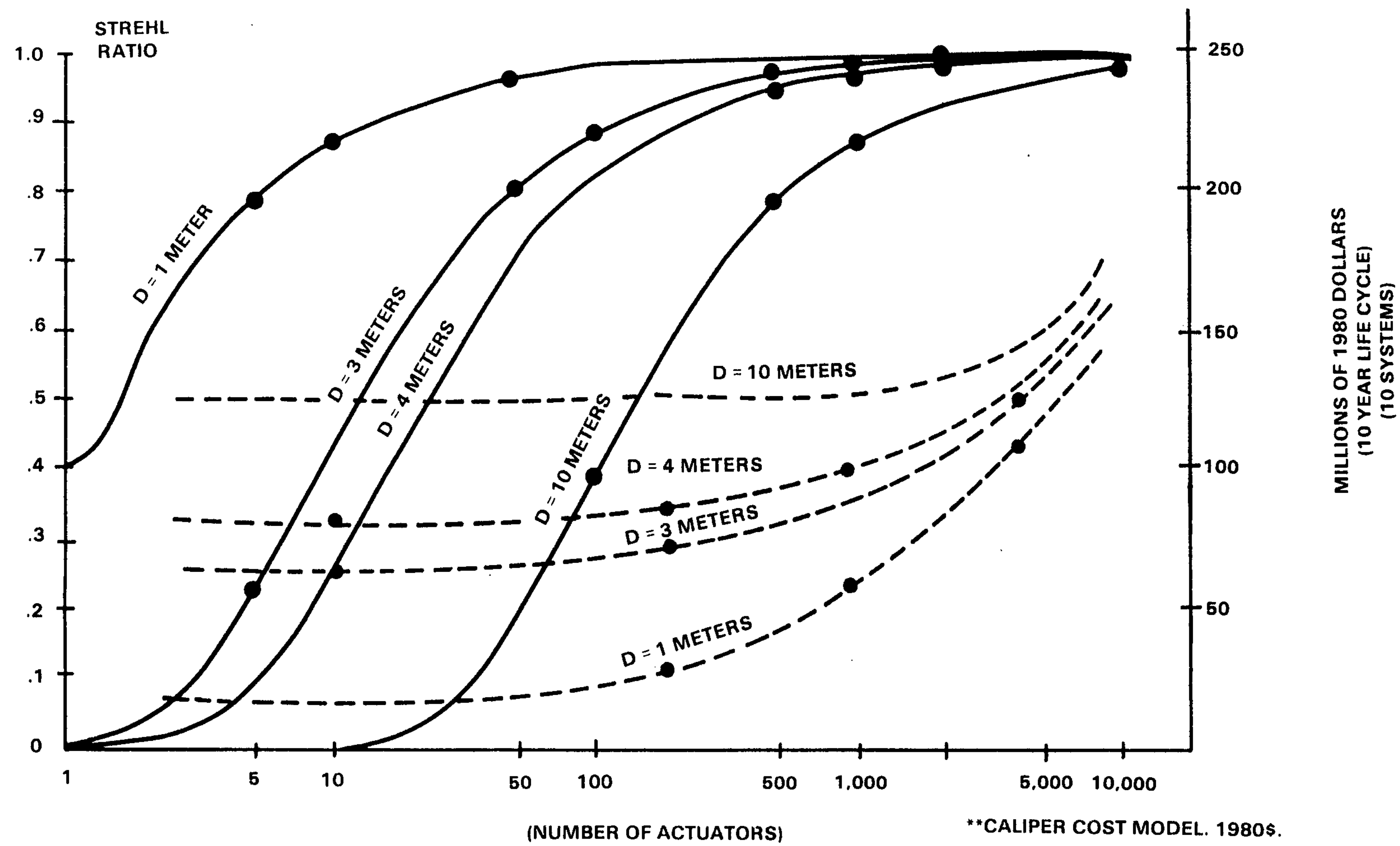
For small diameter optics, the number of actuators is a significant cost driver. For diameters larger than a few meters, the physical dimensions of the optical surface, i.e., the cost of fabricating large mirrors, becomes the most significant cost driver. For diameters of about 10 meters, the life-cycle cost is essentially independent of the number of actuators. This suggests that for NASA missions where large diameter optics are required, the adaptive nature of these optical systems will not add much to the basic cost of fabricating the mirrors themselves. This also suggests that there exists an optimum performance cost-effectiveness trade-off between optics diameter and number of actuators.

An example of how to use this chart is as follows. If a performance figure of a Strehl ratio of 0.9 is required, this can be achieved with an optical system of either 3 meter diameter with about 120 actuators or 4 meter diameter with about 220 actuators. The 10-year life-cycle cost for 10 units of the 3-meter system is about 60 million dollars versus 80 million dollars for the 4-meter system.

More importantly perhaps is the apparent lack of cost sensitivity to increases in the number of actuators for optical systems on the order of a few meters in diameter. Yet the increase in performance as measured by the Strehl ratio is significant. For example, given a 70 million dollar life-cycle cost for ten 4-meter optical systems, as measured on the relatively flat dotted curve, one could incorporate up to 100 actuators in each system without much cost increase over 5 or 10 actuators per system. The reason for this is largely due to the overriding difficulty of figuring and polishing very large optical surfaces. This difficulty becomes increasingly acute for shorter wavelengths.The Strehl ratio, however, as measured on the solid curves increases from 0.28 with 10 actuators to 0.82 with 100 actuators, indicating a much higher performance optical system for virtually the same number of dollars.

Again we caution that the cost model has been extended beyond its proven range of validity to obtain these estimates.

ADAPTIVE OPTICS COST



**CALIPER COST MODEL. 1980$.

LASER SYSTEM COST KEY POINTS

> NASA should develop life-cycle cost models for large, long-running, short wavelength lasers (ground-based and space-based) and large diameter space-based adaptive optical systems.

Current laser cost models such as CALIPER II and SLLICC use cost estimating relationships that are based on data obtained from development costs of relatively small laser and optical systems. Use of these models to estimate costs for laser systems significantly larger than 3 to 5 megawatts and one meter optics should be approached with caution.

Note should also be taken of how operations and support costs are calculated in these models. These costs can be a large part of the total 10-year life-cycle cost of any system. These cost models use Air Force regulations and logistic support guidelines to cost operations and support phases of a system development and acquisition program. Thus, the salaries of personnel required by Air Force regulations and the specific peculiarities with regard to support for DoD military systems are inherent in the model projections. These constraints and limitations may not apply to operation and support of NASA civilian applications.

With these caveats in mind, it appears that laser device research and development costs can be expected to be in the range of a few hundred million dollars for 10 megawatt systems. One could expect to increase total 10-year life-cycle costs for these devices by at least 50 percent if a space-based system is required.

Ten-year life-cycle cost of space-based lasers appears to be a factor of two to three times more expensive than ground-based laser systems on a per-unit basis. This increased cost does not include any consideration for on-orbit maintenance or resupply of laser fluids for long-run time applications. Launch costs for fluids required for run times of more than a few tens of minutes can be shown to be prohibitive based on the efficiencies and specific powers of DoD laser systems currently under development.

LASER SYSTEM COST KEY POINTS

- CURRENT LASER COST MODELS ARE NOT DESIGNED TO PROJECT COSTS FOR LARGE LASER SYSTEMS.
- AIRBORNE LASER DEVICE R&D COSTS (NO OPTICS) APPEAR TO RANGE BETWEEN 100-200 MILLION DOLLARS FOR 10MW SYSTEMS.
- IT COSTS ABOUT 50 PERCENT OF THE TOTAL 10-YEAR LCC TO PLACE A SPACE-BASED LASER SYSTEM ON-ORBIT.
- SPACE-BASED LASERS APPEAR TO BE A FACTOR OF 2 TO 3 TIMES MORE EXPENSIVE THAN GROUND-BASED SYSTEMS ON A PER-UNIT BASIS.

4504/80W

ADAPTIVE OPTICS COST KEY POINTS

NASA should develop life-cycle cost models for large diameter space based adaptive optical systems.

There is a trade-off in the cost of adaptive optical systems between increased performance using a larger number of actuators versus larger collector and projector diameters. Twice the dollars provides three times the optical diameter for a given optical performance in terms of Strehl ratios. Thus, the cost for an increase in system flexibility, i.e., three times the range which can be achieved with three times larger diameter optics, may be justified in a cost-effectiveness analysis for specific applications. An additional factor in this type of cost trade-off is the apparent decrease in the cost sensitivity to numbers of actuators as mirror diameter increases. This must be carefully analyzed and verified.

ADAPTIVE OPTICS COST KEY POINTS

- TWICE THE DOLLARS PROVIDES THREE TIMES THE RANGE, I.E., AN INCREASED SYSTEM FLEXIBILITY INHERENT IN LARGER DIAMETER OPTICS.
- THE COST SENSITIVITY TO NUMBER OF ACTUATORS DECREASES AS MIRROR DIAMETER INCREASES.

4504/80W

VI. SYNERGISM OF DOD AND NASA TECHNOLOGIES AND MISSIONS

4504/80W

SYNERGISM OF DOD AND NASA TECHNOLOGIES AND MISSIONS

> Potential applications of lasers in space cover a broad gamut of possibilities having important consequences in both civilian and defense spheres. It is important to understand the similarities and differences in the required technologies for these applications in order to plan for future research and development.

The primary interests of the present study are civilian high energy laser applications -- particularly laser propulsion and power beaming. Less than one percent of total U.S. HEL technology development funding to date has been directed toward applications specifically in the civilian domain, however. There is, nevertheless, a widespread belief that the Department of Defense will develop the needed technologies for all HEL applications, leading eventually to major benefits for civilian programs. To explore whether this is true, it is necessary to survey all presently identified major space laser applications to identify similarities and differences of their technological requirements.

Although the details of DOD laser applications are classified, there has been widespread publication of the possibilities:

(1) Laser beams from space are potentially capable of destroying ballistic war rockets in early stages of flight, long before the deployment of warheads. Lethal light beams travel at least 10,000 times faster than <u>any</u> anti-ballistic missile or projectile. Although the levels of vulnerability of the rockets may be debatable, flying vehicles are inherently fragile and must eventually yield to the deposition of large amounts of destructive energy.

(2) Laser weapons have enormous potential for strategic and tactical strikes against high value targets on the earth's surface. Unlike nuclear weapons, space-based lasers could perform all of these missions with no collateral damage to adjacent civilian populations.

Possible civilian applications cover an even broader range of laser powers and transmission distances than defense applications, however:

(3) At the lower power end of the spectrum of technology requirements are many applications for laser communications and remote sensing.

(4) Higher energy lasers could propel spacecraft with ten times the efficiency of present rockets, opening space for large scale development and exploitation. Ultimately, superpower lasers might efficiently use space relay reflectors to transfer power across many time zones between continents. Native energy resources in the U.S. could thus become exportable to Japan and Europe. The space relay capability could also make feasible energy transmission to utilize the vast hydroelectric potential of the Andes and the Himalayas, eliminating the need for fossil fuels for power generation.

SYNERGISMS AMONG SPACE LASER APPLICATIONS

High applications synergism results from long laser run-time, reduced beam divergence, precise pointing and tracking, and enhanced C^3I.

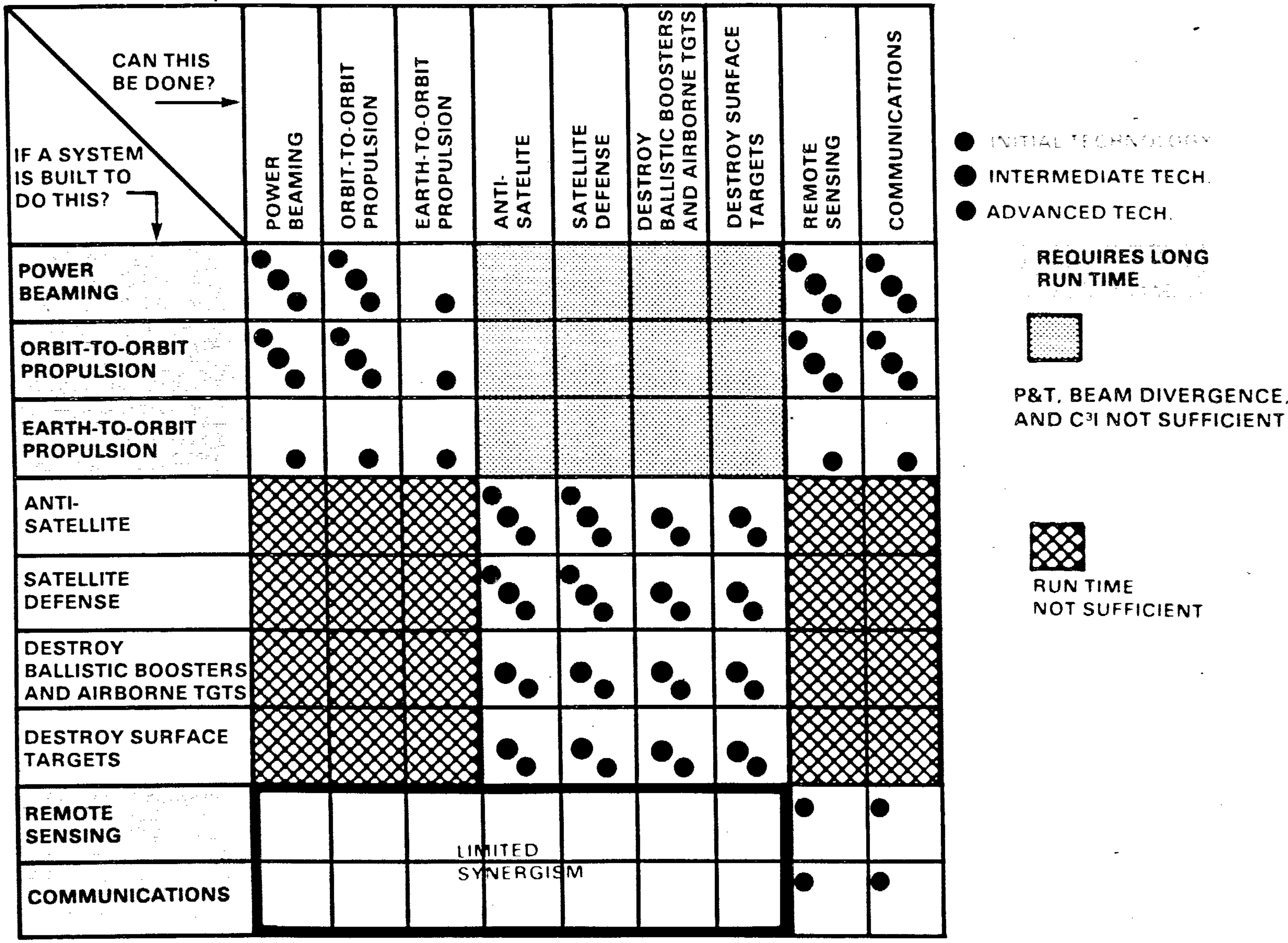
In this chart, which illustrates synergistic potential among a set of civilian and defense applications, the results of detailed analyses of the relvant technologies are unified. This chart provides a concise distillation of what can be done as a function of technological development.

Here the basic question addressed is, "If a system is built to do just one thing, what else might it also be capable of doing?" The same applications are displayed both horizontally and vertically to search for commonality. If an application is feasible at a given technology level, it is indicated by an "X" of the appropriate color. Note that the primarily "civilian" applications are shaded in gold in the left column, calling attention to the fact that they all require a capability for prolonged laser run-duration.

An important observation emerges from analysis of the voids (crosshatched and dotted areas) in this chart: If an HEL system is built just to perform power beaming and laser propulsion functions, the pointing and tracking, beam divergence, Command, Control, Communications, and Intelligence (C^3I) are not sufficient to accomplish the defense applications considered (dotted area). Similarly, if a high energy laser system is built just to perform missions of destroying satellites, boosters, or surface targets, the system run-time is not sufficient for the "civilian" applications considered (cross-hatched area). Thus, either longer running military laser systems or more precise and commandable civilian laser systems increase the potential that a single generic system could perform all the space laser applications considered.

Remote sensing and communications applications are feasible at the initial technology level as indicated. They would have very limited synergism at that level, but there is no justifiable reason to build remote sensing and communications systems using higher technology levels.

SYNERGISMS AMONG SPACE LASER APPLICATIONS



VII. GROUND-BASED TECHNOLOGY ALTERNATIVES FOR NASA MISSIONS

4504/80W

GROUND BASED TECHNOLOGY ALTERNATIVES FOR NASA MISSIONS

There is ample evidence that ground based high energy laser systems can be developed in a shorter time and at lower cost than space based HEL systems. This implies that NASA might take a short-cut to operational space laser capabilities by fully exploiting the ground to space power relay concept.

Our technology assessment holds some clear messages, _viz_:

(1) The chemical lasers which represent the main thrust of the present DoD high energy laser effort are not suitable for civilian applications.

(2) The 5 micron carbon monoxide electric discharge laser was demonstrated in the early 1970's to have the potential for CW operation at very high power levels and 50% "wallplug" efficiency. (It has also been shown by Dinalechev in the Soviet Union to be capable of efficient (>10%) operation at its second harmonic (~2.5 micron) wavelength.)

(3) Free-electron lasers are a very important energy technology that will be highly appropriate for both civilian and defense applications if present experiments reach the expected performance goals. The present estimate of time to achieve 10 megawatt power output is shorter than for any other type of laser.

(4) Cost comparisons for ground based versus space based lasers imply that ground based lasers will be at least three times less expensive.

Taken together, these findings point strongly to a need for NASA to investigate the ground to space "relay" approach in detail. There is ample evidence that NASA can explore new and important research areas not covered by present DoD programs. The enormous electrical capacity of the United States which is available twenty hours a day (excluding the typical four hour peak-load in the afternoon) could become the key resource for full scale development of outer space if laser propulsion and power beaming were fully exploited.

The key technologies required for relay, in addition to large, continuously operating lasers on the ground, are adaptive optical transmitters capable of transmitting an undistorted high power beam to space through the earth's atmosphere and cooperative adaptive optics in space capable of receiving the beam and redirecting it to the utlimate focal point.

AN ALTERNATE OPTION - THE RELAY CONCEPT

Space laser capabilities can be achieved by ground-basing the laser itself and space basing only transfer and projector optics.

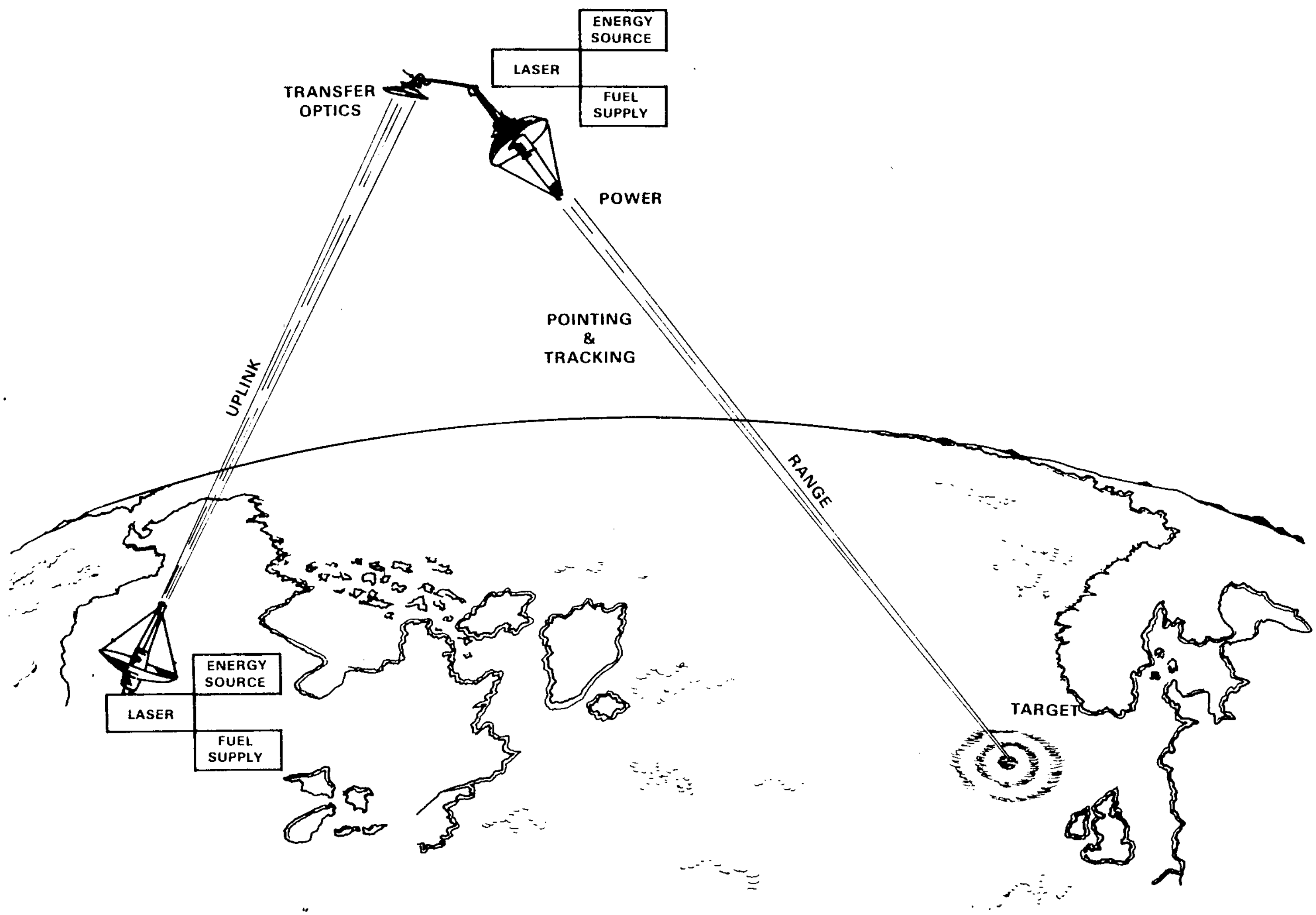
Neglecting for a moment the ground-based projector, the graphic shows laser, energy sources and/or fuel supply deployed in orbit to deliver the required power with the necessary pointing and tracking accuracy over the requisite range to a specified point. An alternate option to achieve this same capability is achieved by the ground-based laser with transfer optics in space that would replace the space-based system. This same generic concept could be used to beam energy across continents in a civilian power beaming system.

The very difficult and expensive problems of refueling cryogenic and corrosive fuels in orbit are eliminated by the Relay approach. Also eliminated are requirements for space-rating hard-to-maintain hardware, lightweight engineering, and achievement of high levels of reliability. Run-time is also increased by the availability of an extended ground-based fuel supply.

Because the primary components of the HEL are located on earth, they can be constructed without regard to weight or volume restrictions. A high power beam might also be delivered to a ground receiver from an ensemble of smaller ground-based HEL's by directing them to a single set of transfer optics in space.

Careful selection of short laser wavelengths can keep atmospheric disturbances of the beam to a minimum and also reduce the size of the required optical transmitter and receiver optics. Orbital altitude for the projector optics can be selected to minimize the number and complexity of optical systems required to provide continuous power to a point on earth.

AN ALTERNATE OPTION — THE RELAY CONCEPT



GROUND TO SPACE RELAY PARAMETERS

> Ten to twenty meter diameter optical systems in geosynchronous orbit can collect 98 percent of the energy from ground-based visible wavelength laser systems.

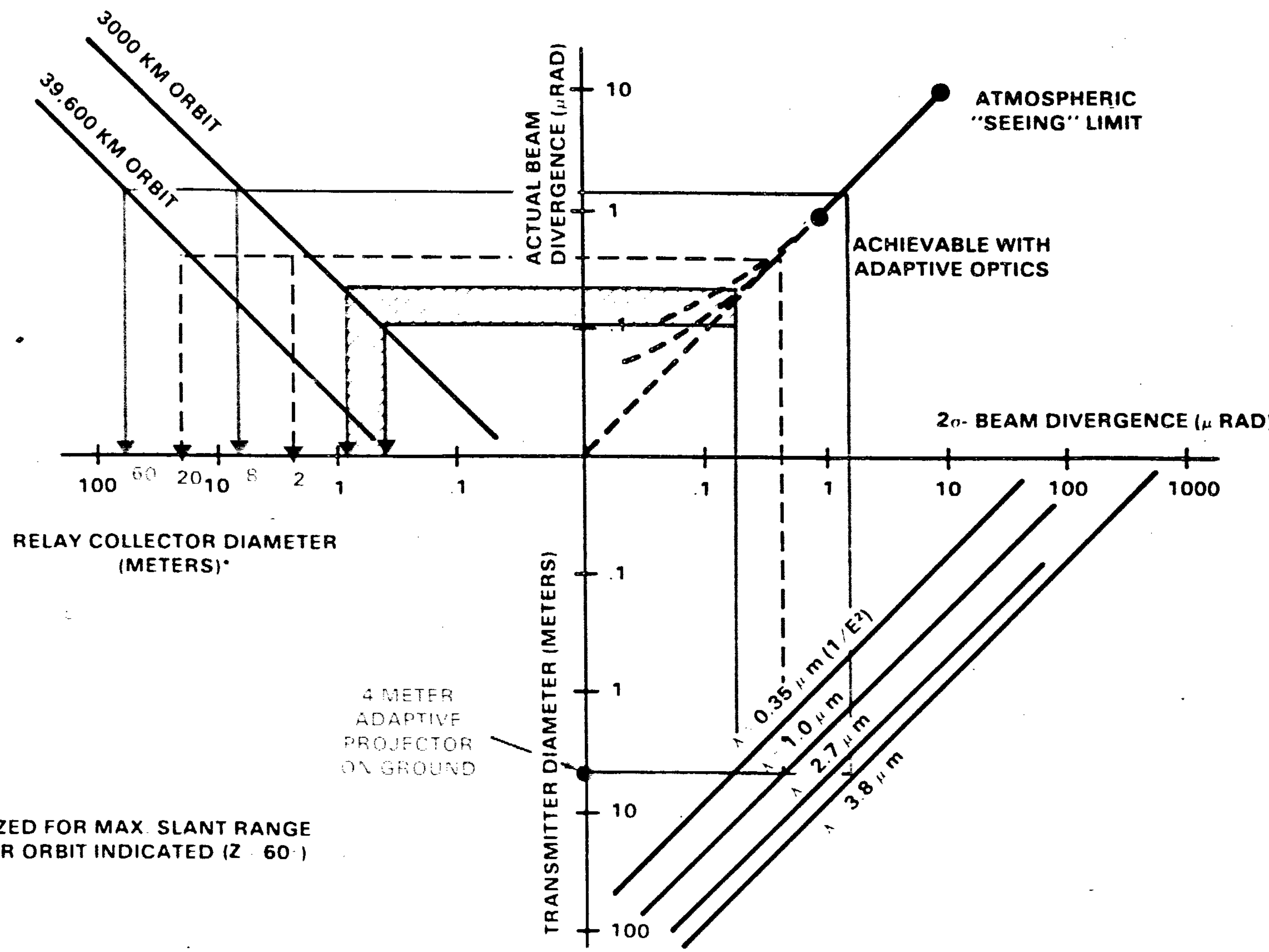
Ground to space relay parameters are presented here in a "carpet plot" format. Ground transmitter optics diameter (along the lower ordinate) is transformed into a 2 sigma beam divergence (along the right abscissa) for a number of transmitted wavelengths ranging from 0.35 micron (Excimer lasers) to 3.8 micron (DF Chemical lasers).

The upper righthand quadrant introduces atmospheric degradation to transform the "optimum" beam divergence (along the right abscissa) to an actual beam divergence (along the upper ordinate) outside the atmosphere. The solid line in this quadrant shows the presently achievable corrections using adaptive optics, while the dashed lines indicate the range of uncertainty for future adaptive optic systems.

The uncorrected atmospheric "seeing" limit of 10 microradians is a well-known phenomenon. There is general agreement that there would be essentially no degradation at a one microradian beam divergence using currently realizable adaptive optics technology. For smaller beam divergence (<1 microradian), there is no general agreement on the degradation that would result from a propagation of short wavelength high power laser beams through the atmosphere. The dashed lines represent a broad range of possible values that could occur depending on the sophistication of the adaptive optical system used and the accuracy of predicting the variables associated with modeling atmospheric parameters.

Relay collector optics diameter required to collect 98 percent of the transmitted energy (along the left abscissa) can be obtained by reflection off the lines for two particular orbital altitudes, 3,000km and 39,600km (geosynchronous). Note that the relay collector diameter is sized for the maximum slant range that occurs at a 60 degree zenith angle.

GROUND TO SPACE RELAY PARAMETERS



*SIZED FOR MAX. SLANT RANGE FOR ORBIT INDICATED (Z 60)

VIII. SPACE-BASED TECHNOLOGY ALTERNATIVES FOR NASA

4504/80W

SPACE-BASED TECHNOLOGY ALTERNATIVES FOR NASA

Ultimately, it is clear that basing lasers in space would be preferable to transmitting energy from the ground. Very lightweight lasers and solar or nuclear high energy power supplies will be essential if this is to become possible, however.

There are countless opportunities for important and original research activities supporting civilian high energy laser applications in space. Since all such applications involve the use of lasers which run for extended periods of time, the use of expendable fuels is out of the question if the lasers themselves are to be deployed in space because this would entail open-ended needs for fuel supply. The only reasonable alternatives are solar and nuclear. Fortunately, it appears that both of these options are feasible. In fact, the possibilities are sufficiently encouraging that certain important avenues of research deserve particular emphasis.

Solar-electric lasers might be powered by photovoltaic or thermal/mechanical generators. These approaches involve familiar problem areas for NASA. A more interesting possibility is that sunlight may be used to directly pump a lasing medium.

The kinetics of several candidate direct-pumped lasers have been examined in detail by several researchers (cf. reference below). The space environment affords uniquely different opportunities for lasing devices from those that are reasonable on the earth. Huge low-weight inflatable concentrators a kilometer in diameter could concentrate sunlight to a chamber a few meters in diameter where a low-gain, benignly circulating medium could produce lasing action with no intermediate steps. Since the laser is comprised mainly of a flimsy, almost empty box, the overall system weight can be suprisingly low. Clever filtering and heat management can further enhance the cost-effectiveness of systems whose predominant cost-driver is the overall system weight that must be placed in space.

Another extremely promising option for efficient high energy lasers in space is afforded by concepts based upon the rotating fluidized bed nuclear reactor (RBR). This device has been a subject of theoretical and laboratory research for fifteen years. It seems to be both safe and ideally suited for the space environment. It appears capable of yielding 10 to 100 megawatts of electrical power from a system having remarkably small overall weight and volume -- quite compatible with Space Shuttle constraints.

Reference: "New Candidate Lasers for Power Beaming and Discussion of Their Applications" by John D. G. Rather in Radiation Energy Conversion in Space, Vol. 61, AIAA Progress in Aeronautics and Astronautics, Kenneth Billman, Ed., 1978.

SOLAR POWERED LASERS IN SPACE

There are several plausible concepts for solar powered lasers in space. Direct solar-pumped lasers may be particularly interesting because of their simplicity, provided that they can be made sufficiently efficient and cost effective.

The "hammer-and-tongs" approach to building a continuously operating high laser system in space would involve the use of some sort of solar powered electrical generator to run a conventional electric discharge laser (EDL) or a free electron laser (FEL). Indeed, this may prove to be a straightforward method if high overall efficiencies can be achieved by such lasers as the FEL (/50%), the CO EDL (/50%), or the Excimer (/15% at short wavelengths). A baseline case CO EDL concept developed by W. J. Schafer Associates has an estimated system mass, of 131,000 Kg for a 100 MW laser*. The four major contributors to the mass of this system are the sunlight collector, the adaptive projector optics, the laser (with its power generator), and the waste heat radiator. In electrical laser systems, the latter two components dominate because the solar concentrator can be of very light construction and the projector optics are relatively minor components of the entire system.

Directly pumped solar lasers are very different in conception. The sun is a large angular source (/0.5 degree) so that the image at the focus of a large concentrator is still large even for very short focal lengths. (A 1 Km diameter concentrator intercepts 1 GW of solar power. A focal ratio of 0.4 yields an image approximately 4 meters in diameter.) Hence, the lasing volume must be large also. This necessitates development of a new class of laser especially suitable for use in space. Interestingly, the power scales with volume of the laser and thus increases as the cube of the linear diameter, while the mass scales with the wall areas which increases only as the square. (The lasing medium is a gas of negligible weight.) Hence, larger devices have better specific weight per megawatt transmitted.

The biggest problem with direct-pumped lasers is that the solar spectrum is very broad, while the absorption lines of most lasing gases are very narrow. Hence, only a small fraction of the available sunlight can be utilized. This equates to low overall efficiency, which seems fatal to the concept at first glance. It is possible, however, to use clever filtering at the primary collector and/or a "black-body Chamber" pumping cavity to improve the effectiveness markedly.

New and important progress is being made in the area of waste heat rejection by A. Hertzberg at the University of Washington. Laboratory experiments have proven the feasibility to reducing the heat radiator mass by a factor of at least ten by allowing the heat to melt a meterial which can be broken into thousands of tiny droplets to achieve very large surface radiation area. This breakthrough should profoundly affect the feasibility of high energy systems in space.

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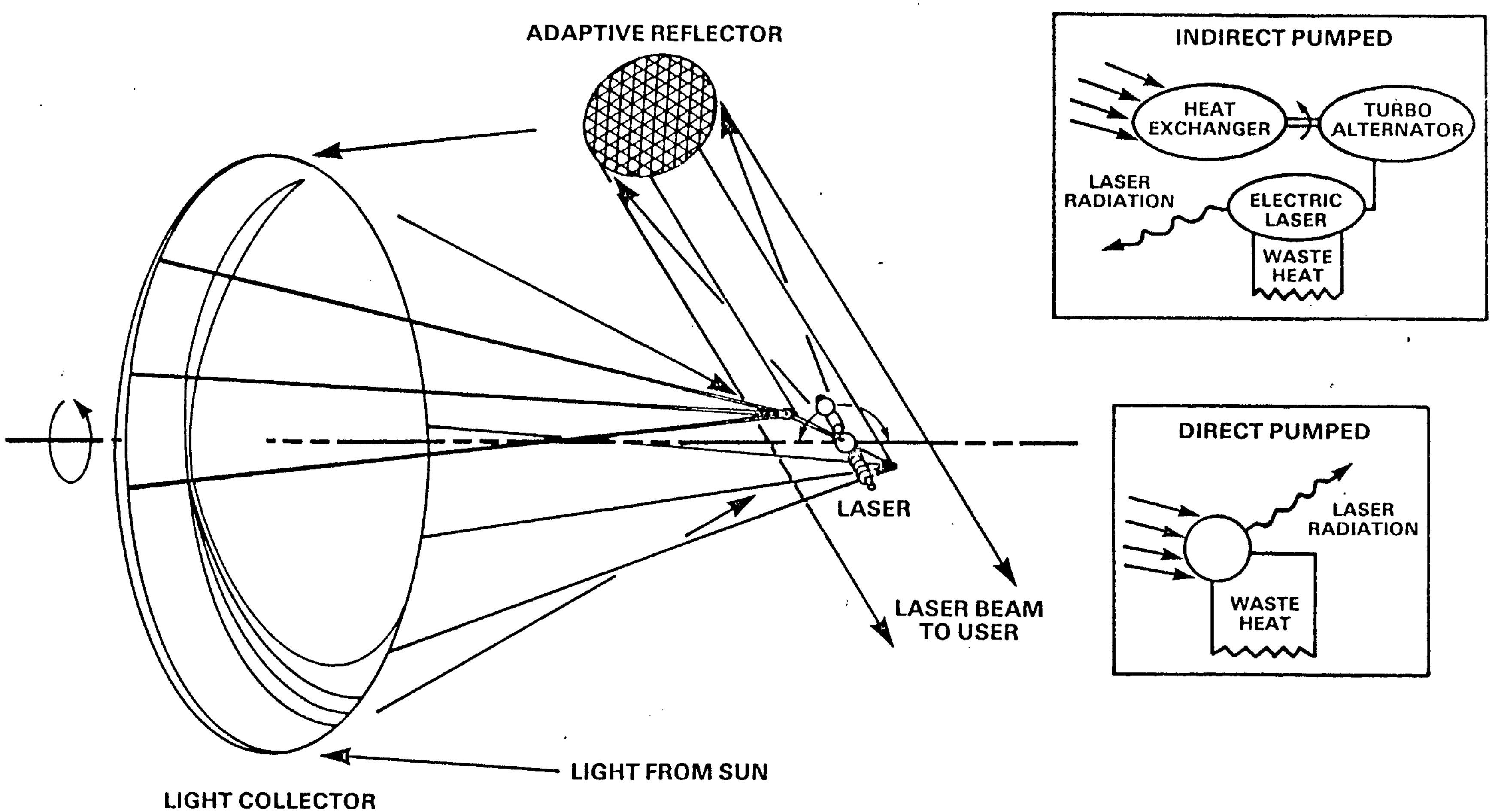
*For an extensive discussion of the physics and engineering of solar powered lasers in space see for example the paper "New Candidate Lasers for Power Beaming and Discussion of their Applications" by John D. G. Rather in Radiation Energy Conversion in Space, V. 61 of AIAA Progress in Astronautics and Aeronautics (1978).

SOLAR POWERED LASERS IN SPACE



ADVANTAGES OF THE ROTATING BED REACTOR (RBR) POWER SOURCE

The Rotating Fluidized-Bed Nuclear Reactor is an outstanding candidate power source for all types of space-based electric lasers.

The RBR was originally conceived in the mid-1960's as an alternate concept for nuclear propulsion in space. Laboratory work was pursued at Brookhaven National Laboratory (BNL) for several years, culminating in a successful cold-flow demonstration of the stability of the rotating fluidized bed of 10 micron diameter simulated fuel particles. Recently work has been reinitiated in a combined effort by BNL and The BDM Corporation to make a case for the RBR as an outstanding option for efficient electric power production in space.

The chart on the opposite page shows some advantages of the RBR concept. In the RBR, enriched Uranium fuel particles are centripetally accelerated by a rapidly rotating, porous metal frit so that the particles are held fixed to the wall by an effective force of about 500 g. A high pressure gas (e.g., hydrogen or helium at 1000 p.s.i.) is introduced radially through the porus frit so that the fuel particles are levitated toward the axis. The resulting fluidized bed of very hot particles has enormous surface area for efficiently transferring heat to the high-pressure gas. The hot gas exits along the axis of rotation, whence it passes through an MHD generator and heat exchanger before being recompressed and reused. Criticality is controlled by rotating rods which reflect neutrons back to the fuel on one side and absorb them on the other side.

The estimated volume and mass for a 10 megawatt, closed-cycle electrical plant is impressively small: less than 5 cubic meters and 27 metric tons (using a conventional state-of-the-art radiator for waste heat). Further mass reduction appears possible by using the new method of heat rejection (molten metal droplets) now being pioneered by Abraham Hertzberg at the University of Washington: estimated mass 16 metric tons for a similar system.

ADVANTAGES OF RBR POWER SOURCE

- HIGH POWER (UP TO 3000 MW(e) PULSED IN A 1-10 M^3 VOLUME)
- CW OR PULSED OPERATION
- POWER TO WEIGHT RATIO IS 2-10 TIMES GREATER THAN CONVENTIONAL COMPACT POWER SOURCES
- HIGH EFFICIENCY
- POTENTIAL INDEFINITE OPERATION (CLOSED CYCLE OR OPEN CYCLE AIR COOLED)
- 0-100% POWER IN LESS THAN ONE SECOND
- POWER OUTPUT MODULATION CAPABILITY
- CAN BE USED IN A VARIETY OF APPLICATIONS WHICH REQUIRE HIGH POWER, HIGH POWER/WEIGHT RATIO SOURCES
- ENHANCES FEASIBILITY OF NEW WEAPONS SYSTEM CONCEPTS

LASER SYSTEM WEIGHT VERSUS RUN DURATION

There is no plausible civilian use for high energy lasers using expendable fuels in space. Open-cycle lasers may be useful for early proof of principle demonstrations, but all operational applications will require closed-cycle lasers.

This is a very important chart. It shows clearly why expendable fuels are not appropriate for any applications requiring high energy lasers in space that must run for prolonged periods of time.

The ordinate of the chart shows total system weight, including fuel, while the abscissa shows required run duration. The y-intercept for expendable fuel devices corresponds to the dry weight of the systems. The Space Shuttle payload limit is indicated by a horizontal line. The two dashed curves show weight versus run time for two large chemical lasers using hydrogen and fluorine as fuels. The solid curves show similar data for two electric discharge lasers using hydrogen and fluorine to run an electric generator. (The power levels are classified.) It can be seen that the system weight exceeds the Shuttle payload limit after only a few minutes of operation. (Note that it is quite unlikely that liquid hydrogen and fluorine fuels would be carried in the Shuttle cargo bay. These fuels yield maximum chemical energy per mole, however, and thus serve as most optimistic examples. Other chemical fuels would weigh more for the same power outputs, leading to shorter run times.)

The additional horizontal lines on the chart show the advantage of other laser concepts for long duration missions. For space-based missions the rotating bed reactor (RBR) permits an electric discharge laser to run for a very extended period at full power. The total system weight with a conventional heat radiator and U_{235} fuel is shown. A new waste heat radiator being developed by A. Hertzberg at the University of Washington could reduce the RBR system weight still further, as indicated.

The bottom horizontal line shows the estimated system weight of a 4 meter relay device in orbit 3000 Km above the earth. The upper line characterizes a large aperture (20 meters) relay device in geosynchronous orbit. Clearly, these relay devices hold much promise for expediting high energy laser missions in space if the ground-to-space relay problem can be solved.

IX. NASA LASER PROPULSION AND POWER BEAMING APPLICATIONS

4504/80W

INTERCONTINENTAL POWER RELAY VIA LASER BEAMS

The practicality and desirability of most energy beaming options will be determined by factors beyond mere technological feasibility. Efficiency, cost effectiveness, time of availability, synergistic applications, and the uniqueness of the potential capabilities must be evaluated.

It is important to realize that "propulsion class" lasers would have major capabilities for beaming power for purposes other than simply propulsion. Parlaying synergistic potentials might have important consequences for laser propulsion cost effectiveness.

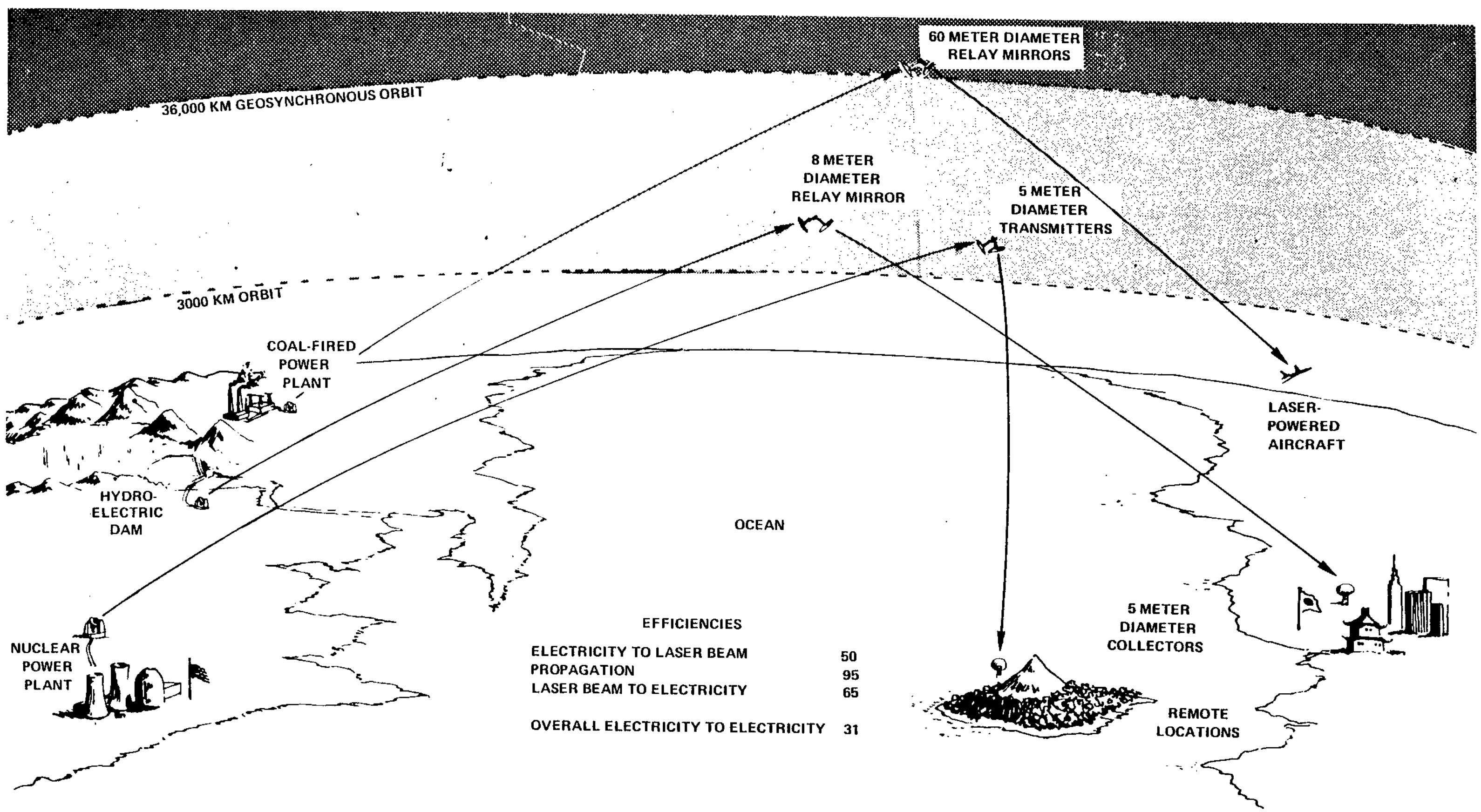
First microwaves and then lasers have emerged as possible candidates for beaming large amounts of energy through free space. Demonstrations have shown that microwaves provide a technically feasible means for efficient energy transmission and reconversion to electric power. The required transmitting and receiving antenna aperture sizes for power beaming are always proportional to wavelength, however and therefore must be very large for efficient long distance transmission of microwave wavelengths (J1cm). Lasers operate at wavelengths around 1cm, with a proportional 10^{-4} reduction in required aperture diameter compared with microwave systems. Hence, the utility of lasers for major power beaming applications appears worthy of serious consideration based upon this one consideration alone. Let us consider some specific examples of potential power beaming techniques that would be of interest if appropriate systems were available

Beaming Power From the Earth to Space for Expanded Civilian and Defense Space Utilization. The extent to which outer space can be used as a resource depends heavily upon the availability of electric power in space. Estimated power demands for several projects currently being considered by NASA imply, even with today's modest projections, a need for many megawatts of power in space in the 1990s. It appears possible to reduce the weight of the power generation system to only 25 to 30 percent of a satellite's total weight if laser power beaming from the earth is utilized.

Relaying Power Over the Horizon Via a Secondary Reflector in Space. A decade ago, Kraft Ehricke proposed that efficient global energy transfer at multi-gigawatt power levels could be accomplished via very large (kilometers in diameter) microwave relay satellites in space. Recent development in laser technology also made laser reasonable conditions for a similar transfer of large amounts of energy.

Lasers near any power plant could potentially relay power safely to small collectors near other power plants anywhere on earth. Consider how coal-generated power from the eastern U.S. could be exported to Europe, Japan, or simply to the west cosast of the U.S. Or consider transferring geothermal or ocean-thermal (OTEC) power from Hawaii to the mainland and hydroelectric power from the Andes to North America. Or, perhaps, consider using power from the wasted natural gas being flared away in Arabia and Mexico at the rate of millions of barrels of "equivalent oil" every day without local pollution to populated areas. Finally, consider the possibility of remote nuclear energy "parks" far from populated areas.

INTERCONTINENTAL POWER RELAY VIA LASER BEAMS



4504/80W

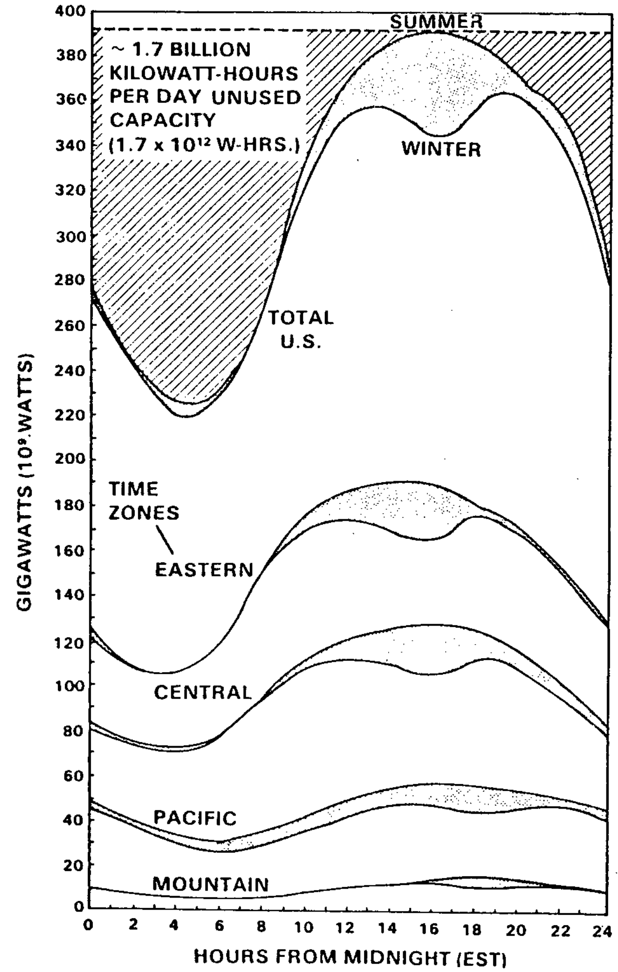
ESTIMATED TYPICAL DAILY ELECTRIC LOAD VARIATIONS FOR THE U.S. IN 1985

> Laser propulsion and power beaming have been criticized as being too expensive because of the need to build billion dollar power plants to support them. In fact, the existing power system is more than adequate.

The question that immediately arises in Power beaming applications is whether the efficiency of the power transfer would be sufficient to make any of these options interesting. Several interacting factors must be borne in mind when seeking an answer to this question, however, because efficiency alone does not make the case. Even if the overall efficiency of the generation, transmission, and reconversion process were only 10%, the United States would still be able to <u>export</u> approximately 100 million KWH of off-peak electricity per day.

The facing chart shows estimated daily electric load diversity for the United States in 1985. The lined area represents unused off-peak capacity of the nation's power plants. It is ironical that new power plants are still being built to satisfy the six hour mid-day peak, while much of the system remains idle off peak. A substantial fraction (>50 GW) of the total capacity will utilize non-fossil energy (nuclear or hydroelectric). Hence, both propulsion and power beaming could be accomplished on a large scale without depleting the nation's fossil fuel reserves. The prospect of exporting power to other countries via relay reflectors in space is interesting to contemplate.

ESTIMATED TYPICAL DAILY ELECTRIC LOAD VARIATIONS FOR THE U.S. IN 1985



ESTIMATED TYPICAL DAILY ELECTRIC LOAD VARIATIONS FOR THE UNITED STATES IN 1985. STIPPLED AREAS INDICATE SEASONAL RANGE. LINED AREA REPRESENTS UNUSED OFF-LOAD CAPACITY.*

4504/80W

*DEVELOPED FROM DATA SUPPLIED BY EDISON ELECTRIC INSTITUTE, NY, NY

COST OF ENERGY TRANSMISSION FACILITIES

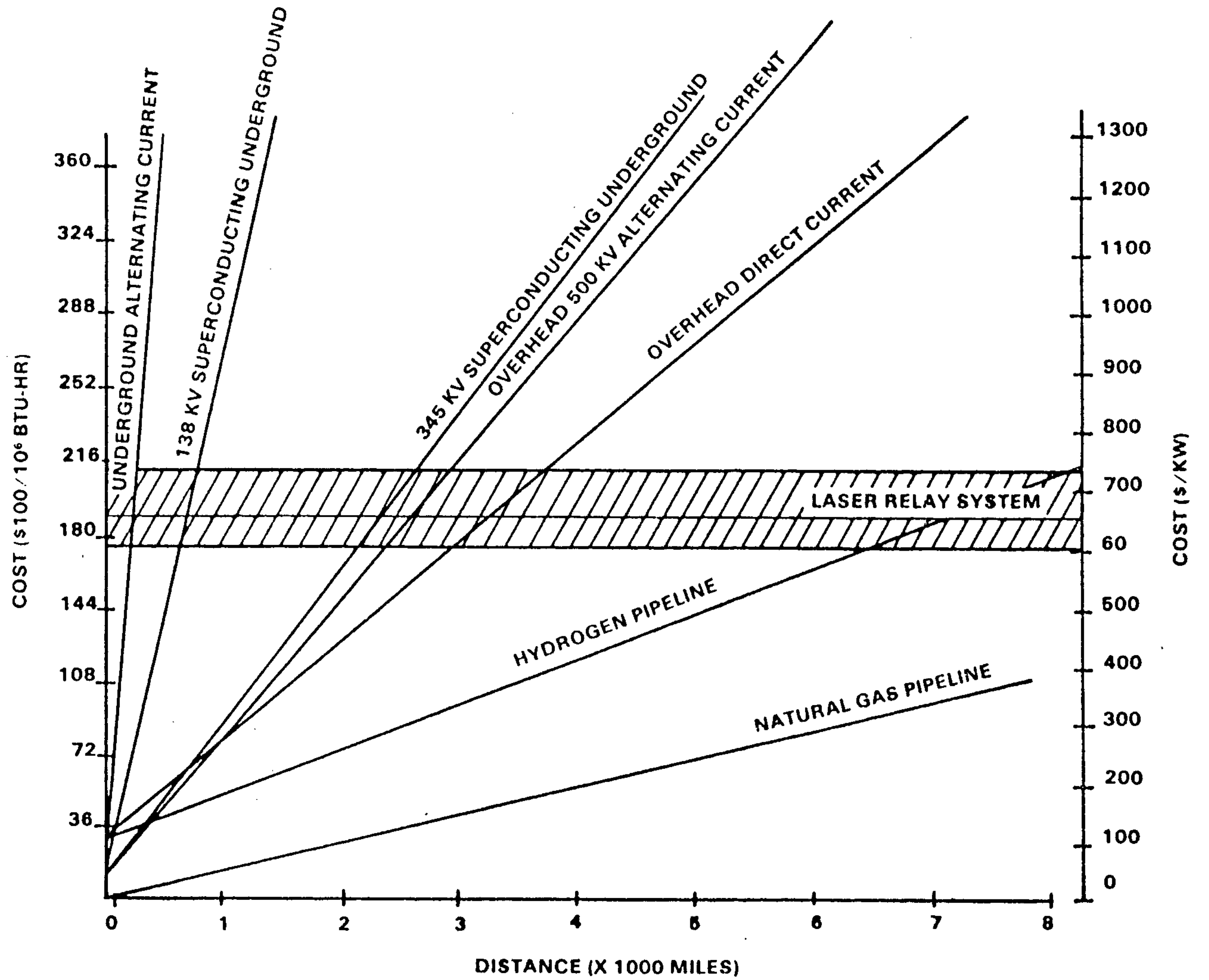
Laser power beaming systems using orbiting optical relays enjoy a relatively constant cost of energy transmission once the relay system is in place. The dollars per transmitted mile appear to be competitive with conventional energy transmission systems for distances greater than 4000 miles.

The costs for developing and placing in orbit large laser and adaptive optical systems have been discussed in previous sections of this report. An alternative in the case of transmitting power has also been discussed, e.g., keeping the laser on the ground and placing reflecting/focusing optical systems in space. As shown, this concept minimizes weight in orbit and greatly reduces total life-cycle cost especially with regard to supply of lasing fluids.

A power beaming system that uses ground-based lasers and orbiting optics incurs essentially no additional cost for increased transmission distance once the relay system is in place. An interesting measure of merit for a power transmission system then becomes dollars per watt as a function of distance transmitted.

This graphic compares the transmission facilities costs of a number of conventional means of energy transmission with a laser power beaming system, using adaptive optic reflectors in 3000 kilometer orbits. The laser relay system appears to be a less expensive means of energy transmission over distances greater than 4000 miles. Additional details such as the cost of energy conversion at the user, reliability of the optical system, etc., must be investigated to further strengthen the case for laser energy transmission.

(U) COST OF ENERGY TRANSMISSION FACILITIES (1979 $)



POWER REQUIREMENT FOR PAYLOAD DELIVERY FROM LEO TO GEO

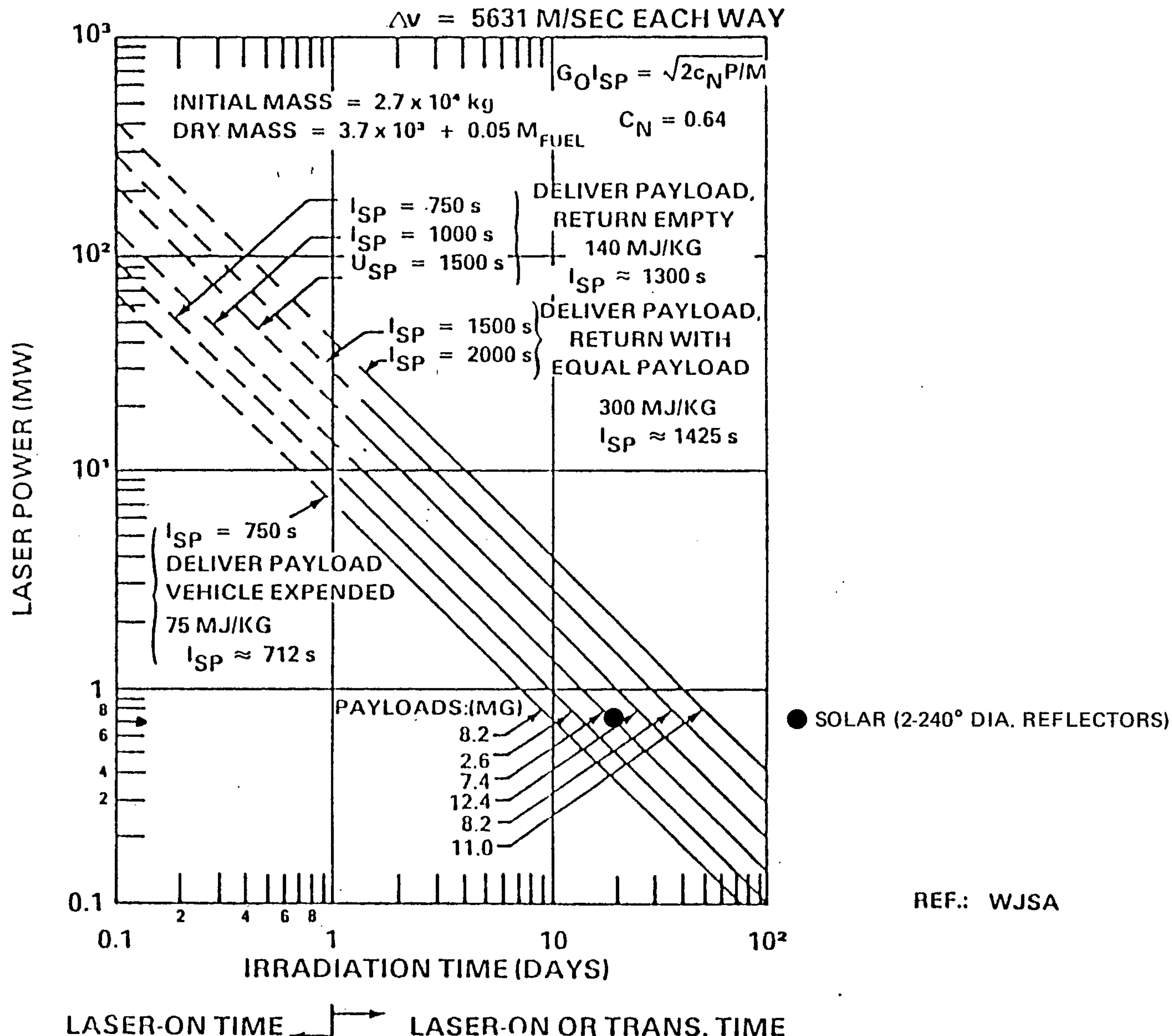
Laser propulsion systems allow the consumption of more energy while using less fuel. A tradeoff is made between a plentiful energy source and the ability to accomplish missions that would otherwise be impossible.

There are a number of parametric approaches to developing plots that can provide a quick-look, "rough cut" at mission potential for laser propulsion systems. Three important parameters that are inextricably included in any representation are the Δv required for a given mission, the laser propulsion system burn time (Δt), and the initital mass of the that system (M_0, which includes payload mass, fuel mass, and propulsion system mass). These parameters can be varied to select a specific set for a given propulsion system design that is a compromise among laser power, mission time, specific impulse, exhaust velocity, payload ratio, speciic power and a seemingly limitless merging of combinations of them. The exact parameters (or sets of parameters) that appear on the ordinates and abscissas of various plots are more a function of a particular analyst's desires than an enumeration of the "classically acceptable" parameters to use. One such plot is shown in the facing graphic which compares the relationship among laser power, runtime, and specific impulse for a range of payloads and delivery options.*

Obviously, there are other propulsion systems that could accomplish the missions indicated here. One such system, a solar powered electric propulsion system using two 240 foot diameter reflectors, is plotted for a specific case, e.g., delivering 7.4 metric tons of payload to GEO and returning empty with a specific impulse of 1000 seconds. This propulsion system can accomplish this mission in approximately 20 days. A laser propulsion system using a 10 megawatt laser could accomplish the same mission in about 1.5 days, as can be seen by progressing up the sloped line to the intersection with the 10 megawatt laser power horizontal line.

* Reference: This plot was prepared by W. J. Schafer Associates, Inc., as part of the NASA/OAST "Theme Team Seven" study in 1976.

POWER REQUIREMENT FOR PAYLOAD DELIVERY FROM LEO TO GEO



REF.: WJSA

Long running high energy lasers provide an exciting option for propulsion systems to perform orbital transfer. Significant payloads can be raised to long-term parking orbits using moderate size laser systems with run times of less than a day.

As previously mentioned, there are many ways to group and plot intersecting system parameters to serve as mission analysis tools. The "first estimate" charts shown on the next two pages show the logical relationships among all of the principal parameters of laser propulsion for orbit changing. The first chart relates laser power to achievable orbital height for specified performance of the laser propulsion engine. The second chart uses a plausible tug model to find the duration of operation to raise a given payload to a given orbital height using the laser power found from the first chart.

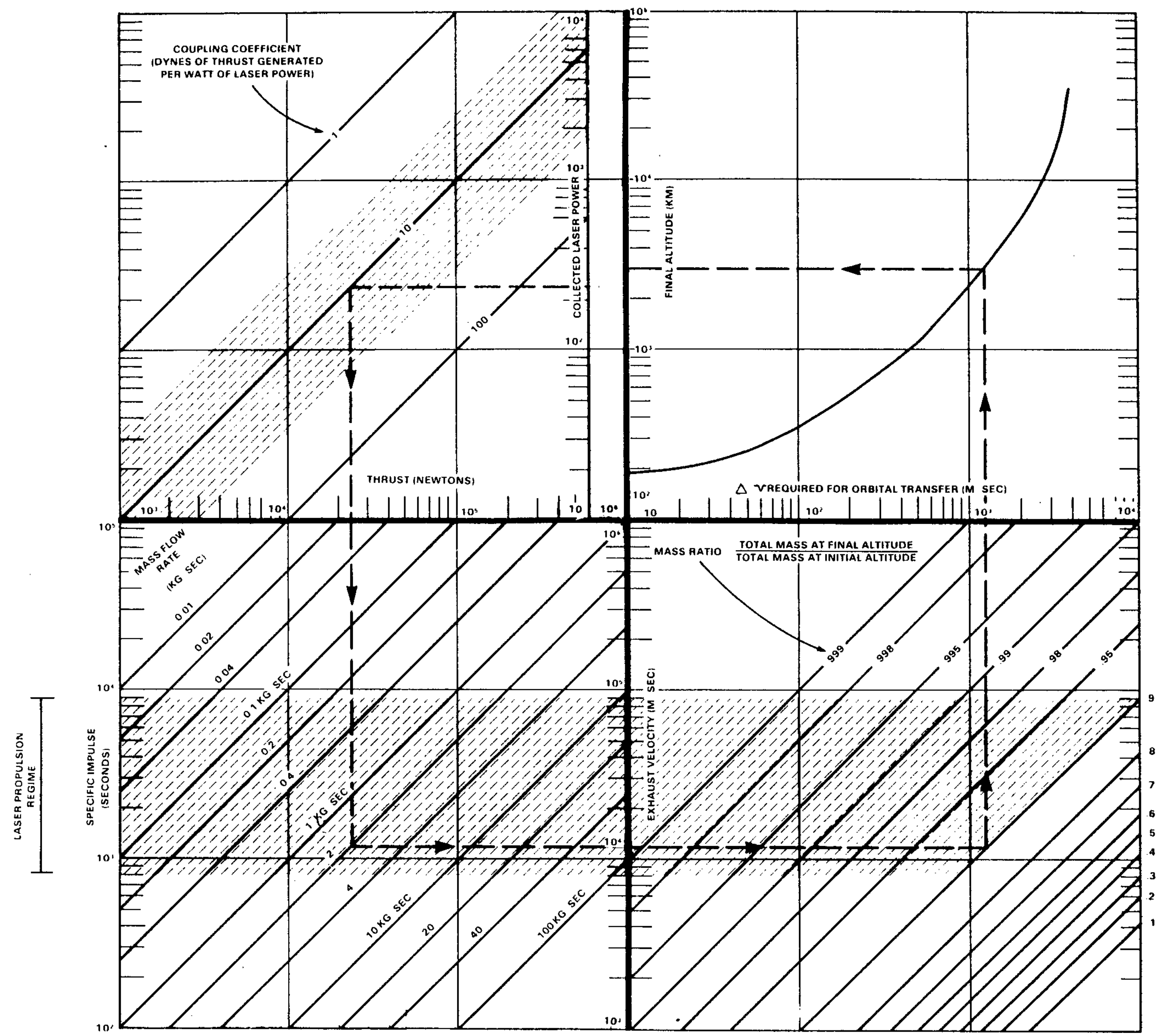
In the upper right hand quadrant, the facing graphic plots the key mission parameter of a given increase in orbital velocity (total Δv) required to deliver any payload from a 185 kilometer orbit to any selected orbital altitude. The remaining curves represent parametric assumptions to describe particular propulsion system options that lead to required laser power (upper left hand quadrant). The significant engine performance parameters are specific impulse, I_{SP}, and the energy coupling coefficient, C, which relates rocket thrust to collected laser power. The chosen combination of C and I_{SP} defines the required fuel flow rate. Knowing what altitude is desired then defines the mass fraction (final-total-mass/initial-total-mass) required to get there. Alternatively, for a specified mass fraction, the chart shows what altitude can be reached.

An example of how to use this plot is shown for the mission of raising a 32 metric ton payload (approximate weight of the expended shuttle main tank) from 185 kilometers to 3000 kilometer orbit using 3.6 metric tons of residual hydrogen and a range of tug-like propulsion systems weighing between 1 and 5 metric tons (i.e., mass fraction approximately 0.9). Exhaust velocity for this example is selected as 10,000 meters per second, corresponding to a thrust of 23,000 Newtons, and the coupling coefficient is chosen to be C =12 dynes per watt. If these assumptions comprise a valid propulsion system, then the total power required is approximately 200 megawatts.

Stippled areas have been added to the chart to designate areas of validity or plausibility. The chart may not be accurate to within 10 percent for mass ratios lower than 0.9 because the fuel mass is sufficiently large that it will affect optimum mission paramters (see next chart). The other boundaries of the stippled areas indicate a plausible regime vis-à-vis achievable physics.

To go further, we must adopt a model of the laser tugboat. The mass of the tug is primarily related to the thrust, both because of the size of the engine and pumps and because of the required stress bearing components of the system as a whole. (Interestingly, the laser light collectors will have the same diameter regardless of the thrust for a specified laser wavelength.)

LASER PROPULSION APPLICATIONS
PARAMETERS FOR ORBIT RAISING FROM 185 KILOMETERS



NASA LASER PROPULSION APPLICATIONS (CONTINUED)

TRW* has modelled a laser propelled tug which seems to have plausible and justifiable characteristics. For our purposes here, we have adopted the TRW tug model as expressed by the equation on the facing chart. We also assume that the fuel mass will, in general, be a small fraction of the tug plus payload mass (<10%).

It is important to understand that this chart is "slaved" to the chart on the previous page. The same thrust, altitude, and laser power must be used here that were chosen on the previous chart. In addition, the laser engine conversion efficiency is closely related to the coupling coefficient on the previous chart for a given engine design. Fifty percent efficiency is regarded as a reasonable value. With these constraints we can then find the total thrust time to perform the mission.

The dashed line applies to the mission of raising the Space Shuttle main tank to a 3000 kilometer orbit from 185 kilometers. It can be seen that this mission can be accomplished in ∿3500 seconds of thrust time with 200 megawatts of delivered laser power. Or, retracing all of the steps, we find that the same mission can be performed in ∿26,000 seconds (7.2 hours) with 20 megawatts of laser power.

* Reference: M. Huberman et.al., "Investigation of Beamed Energy Concepts for Propulsion", Volume 1, by TRW Defense and Space Systems Group, prepared for AFWL, Edwards AFB, CA, October 1976.

PERFORMANCE PARAMETERS OF LASER ORBITAL TRANSFER VEHICLE